



# **DNAPL Detection and Characterization Techniques**

**GeoTrans, Inc.**

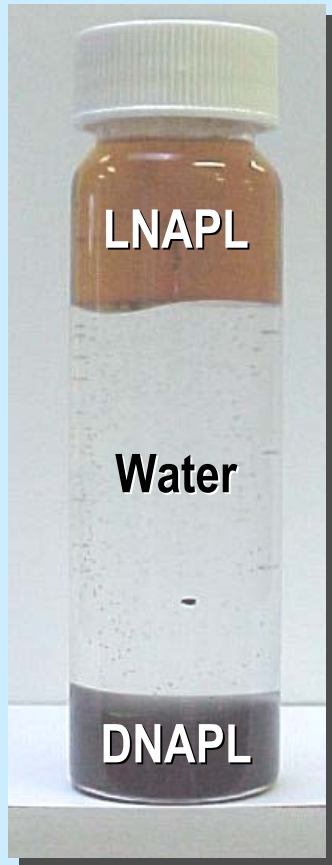


# Presentation Overview

## ■ Definitions

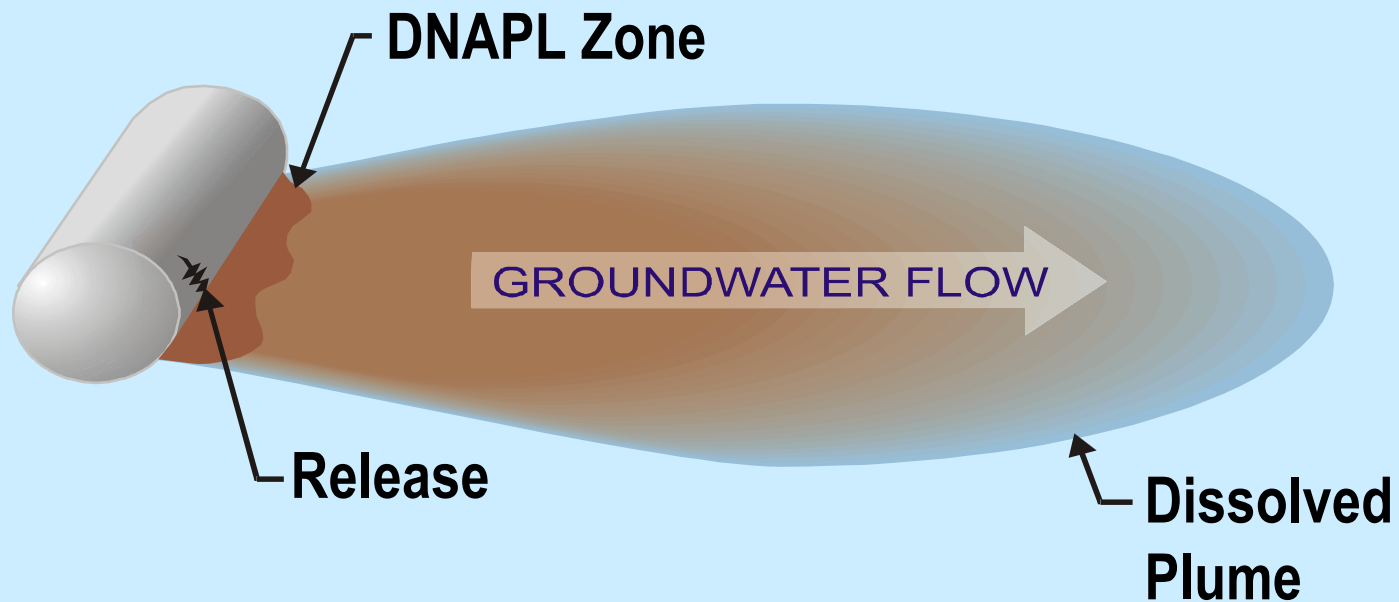
- Why is DNAPL an Issue?
- Regulatory History and Status
- Strategies for Detection and Characterization
- Tools for Characterization
  - Noninvasive
  - Invasive
- Summary

# Definitions



- DNAPL – Dense nonaqueous phase liquid
  - Chemicals with densities greater than that of water and aqueous solubilities that are (generally) low
  - Chlorinated solvents
  - Creosote/coal tar
  - PCBs
- DNAPL entry location; DNAPL zone (includes DNAPL, sorbed chemicals and diffused chemicals); dissolved contamination zone

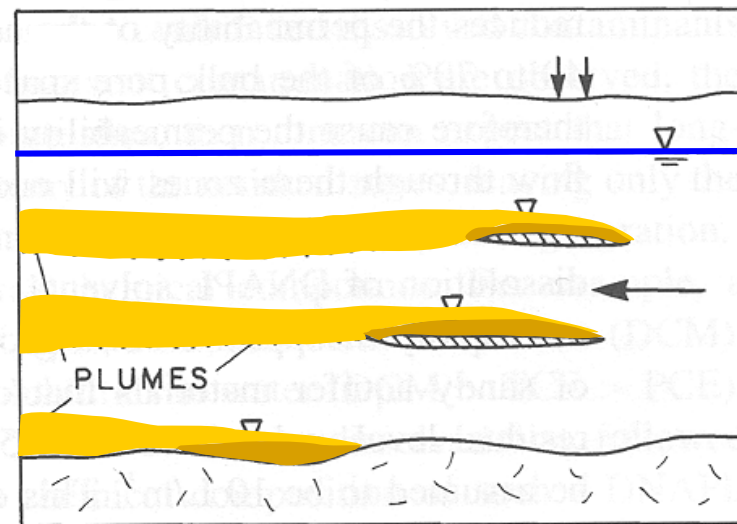
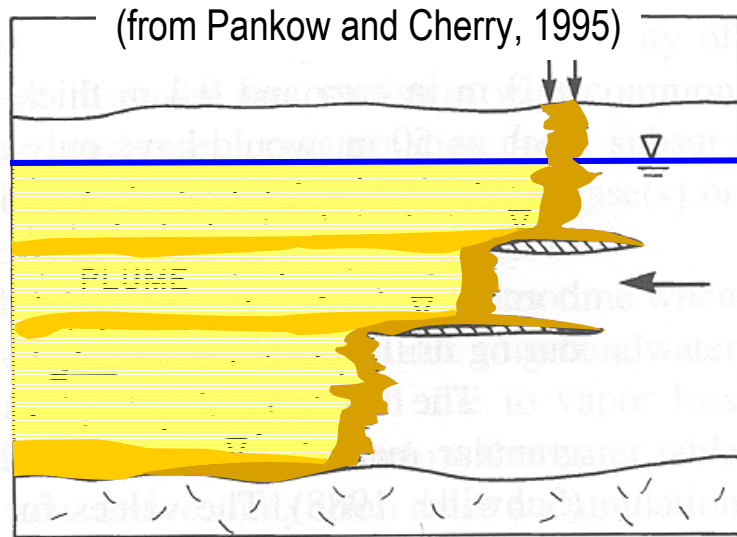
# Conceptual Site Schematic



# Forms of DNAPL

- **Free-phase (mobile) DNAPL** that is under positive pressure and can drain to a well
  - Could be currently moving or contained in a stratigraphic trap
- **Residual DNAPL** (discontinuous blobs and ganglia) that is held under capillary pressure (related to fluid interfacial tension) that will not drain to a well
  - Makes it difficult to find

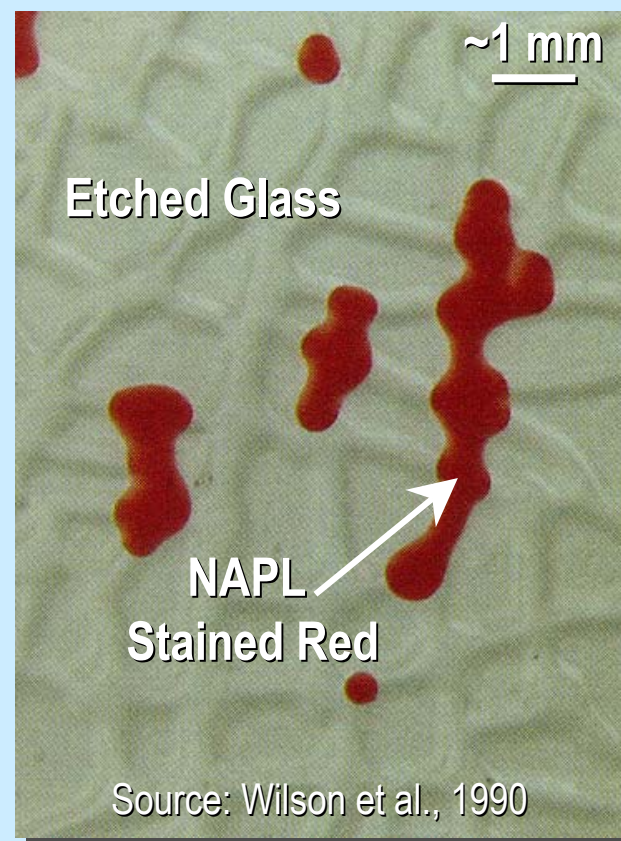
# DNAPL in Pools



- Less contact with flowing groundwater than DNAPL at residual saturation
- Dissolution also limited by weak vertical dispersion
- Greater DNAPL volume in pools
- Thus, the rate of dissolution is reduced and the DNAPL lifetime is extended compared to where DNAPL is dispersed at residual saturation

# DNAPL at Residual Saturation

- During migration, a significant portion of DNAPL is retained in porous media due to capillary trapping.
  - Vadose zone: 10% – 20% typical
  - Saturated zone: 10% - 50% typical
  - Field sampling volume problem
- DNAPL at residual saturation remains immobile unless it is replenished by new releases or subjected to increased hydraulic force.
- Because it will not flow to a well, DNAPL is difficult to detect.



# Presentation Overview

- Definitions

- Why is DNAPL an Issue?

- Regulatory History and Status

- Strategies for Detection and Characterization

- Tools for Characterization

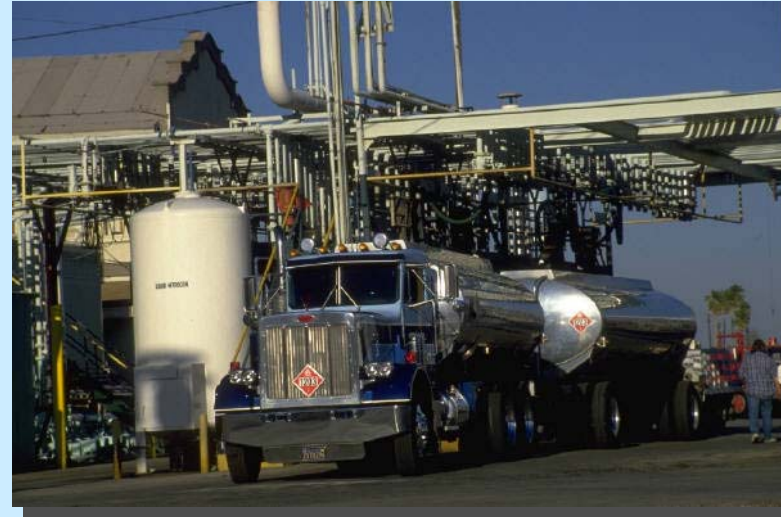
  - Noninvasive

  - Invasive

- Summary

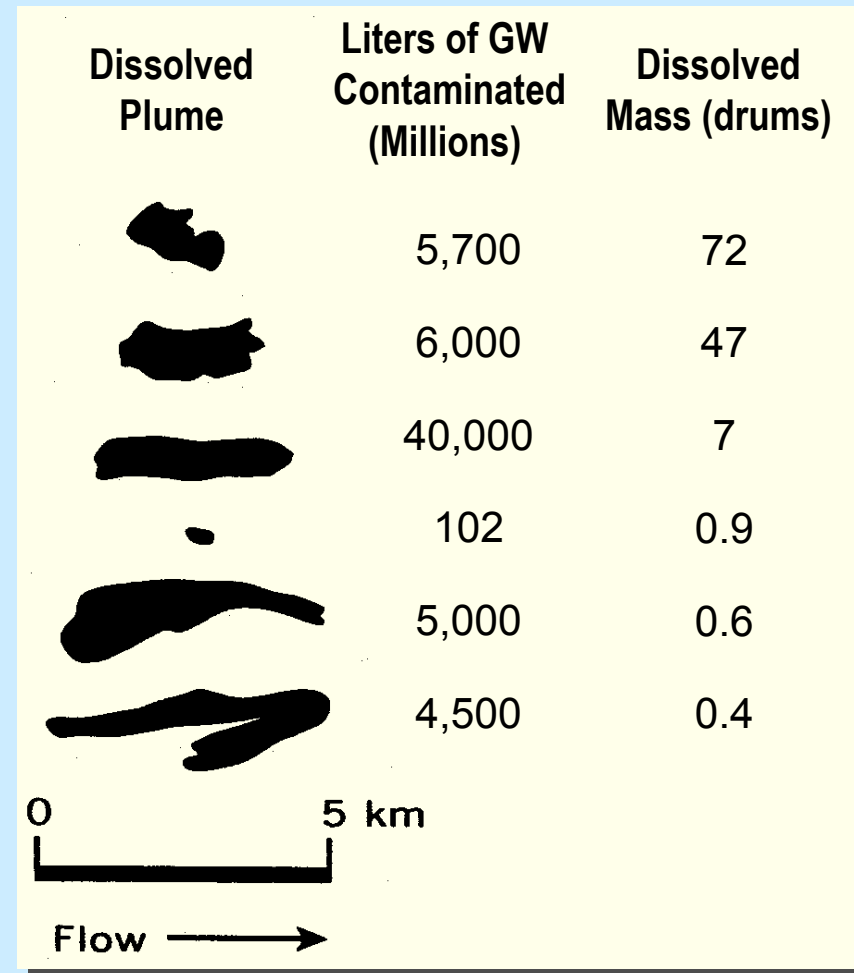
# Why is DNAPL an Issue?

- Widespread production, transport, use, release, and disposal of DNAPLs, particularly chlorinated solvents
- Uses include military equipment manufacturing and maintenance, vapor degreasing operations, dry cleaning, and septic tank cleaners
- Potential for groundwater contamination high due to DNAPL chemical toxicity, persistence, and migration potential
- Chlorinated solvents among the most prevalent contaminants detected in groundwater supplies and at waste sites



# Why is DNAPL an Issue? (cont.)

- Chemical solubilities much greater than MCLs (small DNAPL volume can produce large dissolved plume that does not readily degrade)
- DNAPL source **difficult** to locate and characterize
- DNAPL removal difficult and costly (complete removal **may be impossible** at most sites)
- No DNAPL site has been cleaned up to MCLs



(after Mackay and Cherry, 1989)

# High Potential for Groundwater Contamination

DNAPL	Millions lbs made in U.S. 1990	S.G.	Viscosity (cP)	Solubility (mg/L)	MCL (mg/L)	Ratio of Solubility to MCL
1,2-DCA	13,800	1.24	0.80	8,690	0.005	1,738,000
1,1,1-TCA	802	1.34	0.83	1,360	0.200	6,800
DCM	461	1.33	0.43	20,000	0.005	4,000,000
CTET	413	1.59	0.97	800	0.005	160,000
PCE	372	1.62	0.89	150	0.005	30,000
TCE	165	1.46	0.57	1,100	0.005	220,000
Water		1.00	1.00			

S.G. = specific gravity

cP = centi-Poise

## Chemical Safety Data Sheet SD-14

ADOPTED 1947

# TRICHLOROETHYLENE



### PROPERTIES

ESSENTIAL INFORMATION FOR SAFE HANDLING AND USE

## TRICHLOROETHYLENE

### WARNING! VOLATILE SOLVENT

Use with adequate ventilation.

Avoid prolonged or repeated breathing of vapor.

Avoid prolonged or repeated contact with skin.

Do not take internally.

## 7. WASTE DISPOSAL

7.1 Residue may be poured on dry sand, earth, or ashes at a safe distance from occupied areas and allowed to evaporate into the atmosphere.

8. HEALTH HAZARDS AND THEIR

# Presentation Overview

- Definitions
- Why is DNAPL an Issue?
- Regulatory History and Status
- Strategies for Detection and Characterization
- Tools for Characterization
  - Noninvasive
  - Invasive
- Summary

# Regulatory History and Status

- Studies of pump-and-treat systems in the 1980s showed that suspected DNAPL sites were not being restored at predicted rates
- This led to the concept of Technical Impracticability (TI) waivers in 1993
  - U.S. EPA Directive 9234.2-25
- Since 1993, only about 50 TI waivers have been granted

# Technical Impracticability

- "EPA expects ...all reasonable efforts will be made to identify the location of source areas through historical information searches and site characterization efforts."
- "appropriate level of effort for source removal..."
- "Even partial removal of contaminant sources..."

# TI Waiver

- Characteristics of a TI waiver in 1999 (Region 9)
  - Creosote DNAPL, with high viscosity, is naturally contained in topographically low troughs on a shallow clay.
  - The downgradient dissolved plume is small and is biodegrading (plume is not expanding).
  - A review of remedial technologies indicated that no technology was capable of removing all DNAPL; therefore, it was technically impracticable to restore groundwater quality in the creosote DNAPL area.
  - Region 9 required submittal of a TI evaluation that strictly adhered to the EPA Guidance Document. Three submittals (an original and two revisions) were required before the TI waiver was granted (included approval by Headquarters).
  - Note: TI waivers are very dependent on the EPA Region and other nontechnical factors.

# NFESC

## DNAPL Remediation Technologies Survey

### Objective

- Collect information on the state of the science with regard to remediation of DNAPL source zones in groundwater

### Benefits to Participants

- Access to final report containing:
  - Technology theory and application
  - Technology performance evaluation and development status
  - Remedial costs and technical practicability/impracticability
- Helping to expand the knowledge base and to identify potential new research areas
- List of technology experts and vendors generated from list of survey respondents



For information and to complete the survey:  
[https://projects.geosyntec.com/navy\\_rocs/](https://projects.geosyntec.com/navy_rocs/)

# Presentation Overview

- Definitions
- Why is DNAPL an Issue?
- Regulatory History and Status
- Strategies for Detection and Characterization
- Tools for Characterization
  - Noninvasive
  - Invasive
- Summary

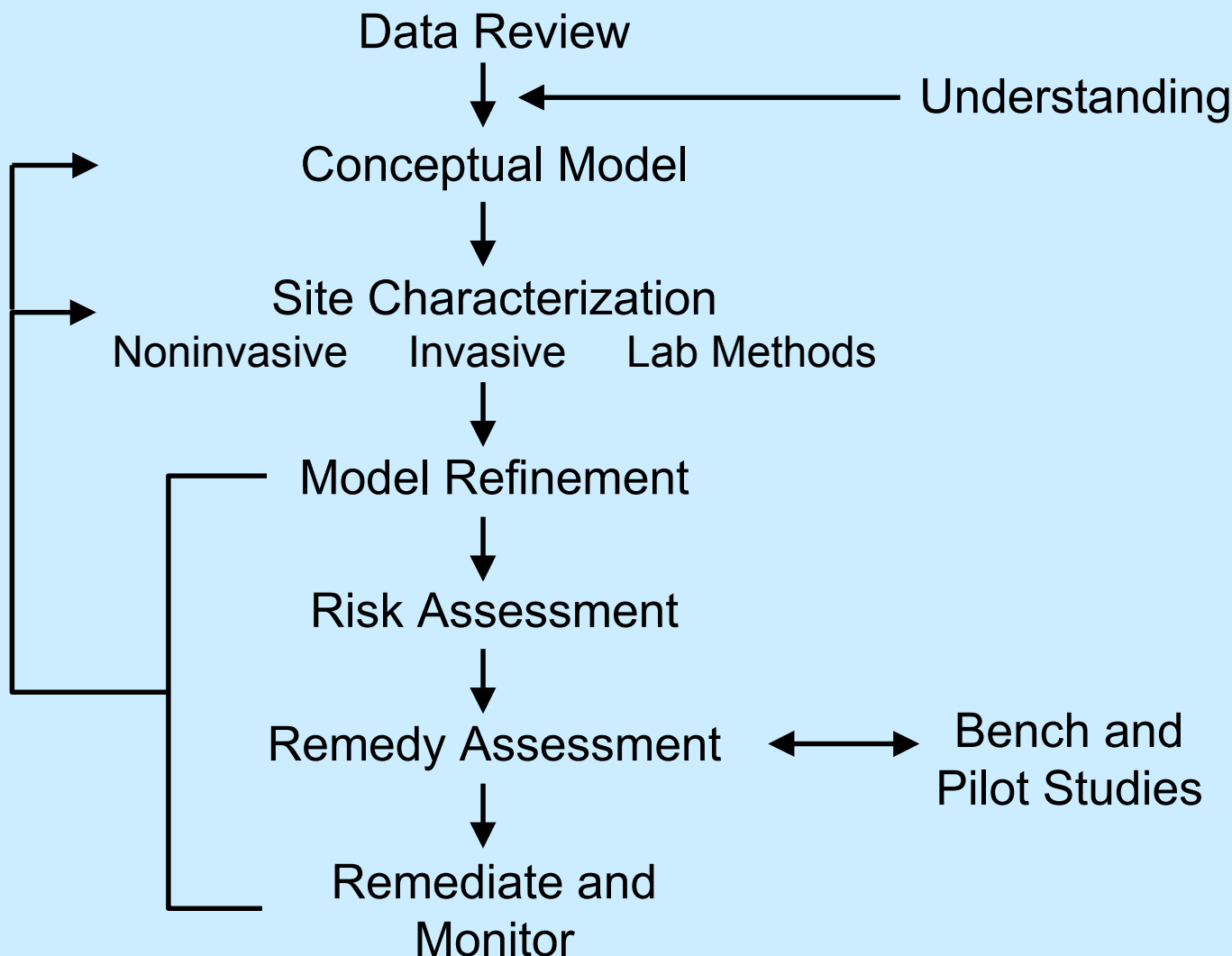
# Strategies for DNAPL Detection and Characterization

- Develop realistic site conceptual model
  - Need to understand stratigraphy
- Use noninvasive information and minimal invasive methods first
- Use plume information to infer up hydraulic gradient source conditions
- Select source investigation methods that provide desired remediation data and minimize risk of mobilization

# Basic DNAPL Characterization Questions

- Is DNAPL present?
- If so, where are the DNAPL sources (e.g., map locations, hydrogeologic units)?
- How long has the DNAPL been in the subsurface?
- What are the characteristics of the DNAPL sources that are important to remediation (e.g., quantity, form, architecture, physical and chemical attributes)?

# Phased Site Management

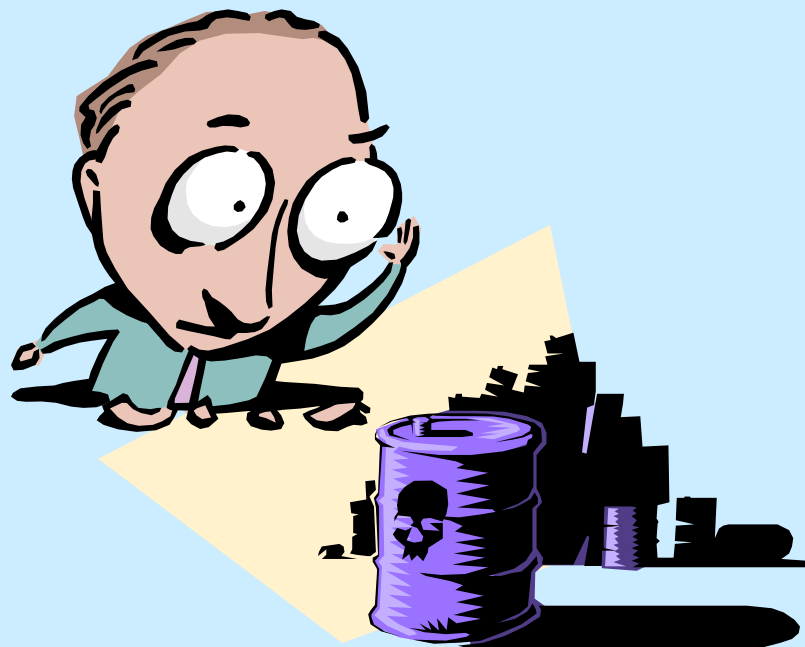


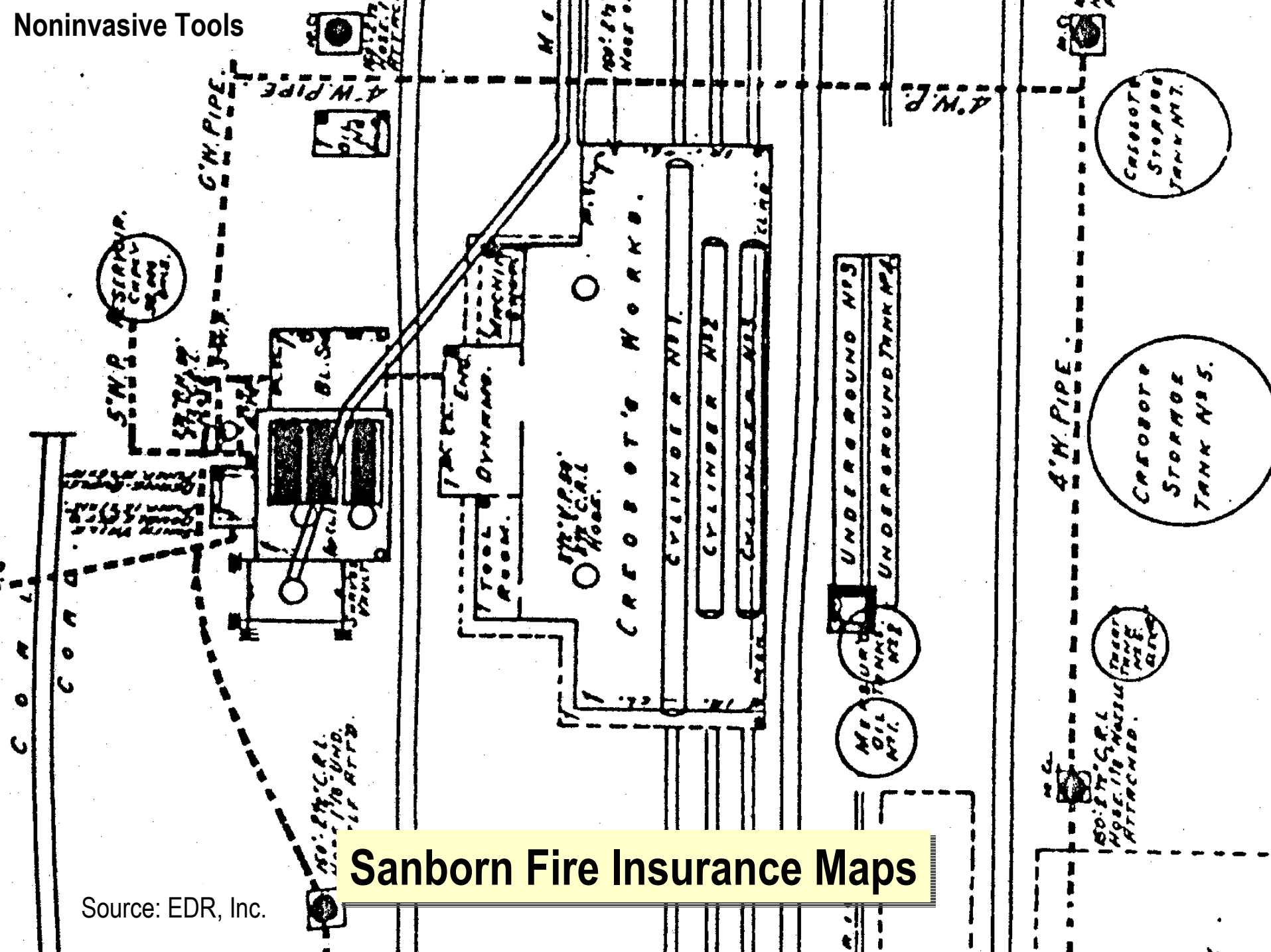
# Presentation Overview

- Definitions
- Why is DNAPL an Issue?
- Regulatory History and Status
- Strategies for Detection and Characterization
- Tools for Characterization
  - Noninvasive
  - Invasive
- Summary

# Noninvasive Tools for DNAPL Characterization

- Site history information (e.g., chemical use, inventory and disposal records)
- Historical aerial photographs
- Geologic fractures/outcrops
- Soil gas analysis
- Surface geophysics
- Site infrastructure information (e.g., sewers)
- Employee/witness interviews





Sanborn Fire Insurance Maps

# Aerial Photographs for Site Investigation

**An inexpensive, noninvasive tool to assess . . .**

- **Historic site use and conditions**

- Source areas
- Land use
- Drainage
- Vegetative stress
- Surface contamination
- Geology
- Relate environmental data to historic site conditions

- **Fracture trace analysis**

- Preferential pathway analysis
- Well siting

# Noninvasive Tools



Love Canal – 1938



Love Canal – 1951

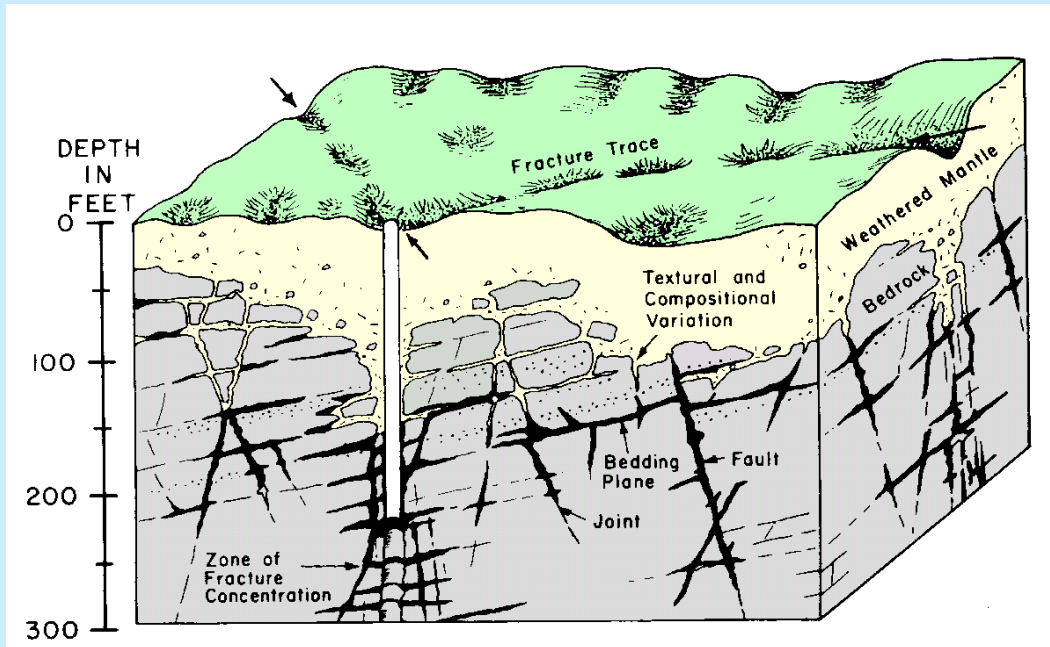
## Noninvasive Tools



- 1966 oblique photo showing the rear end of a metal works facility where groundwater is contaminated by chlorinated solvents



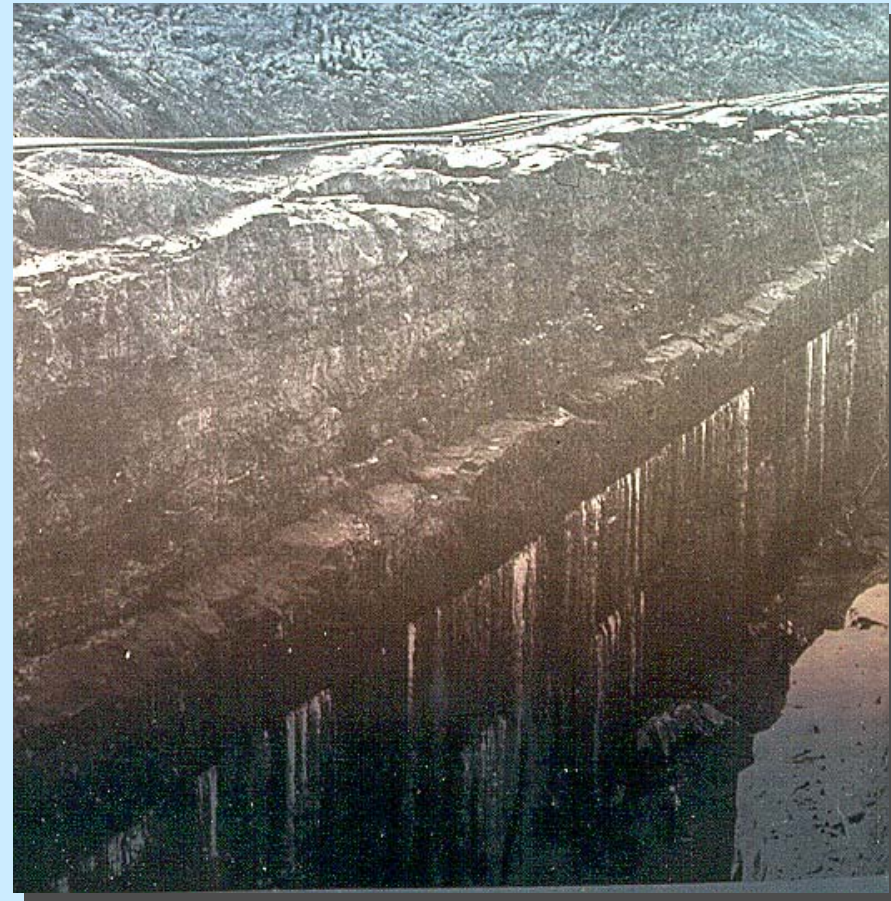
# Fracture Trace Analysis



After Lattman and Parizek. 1964. J. of Hydrology, p.87,  
reprinted with permission of Elsevier.

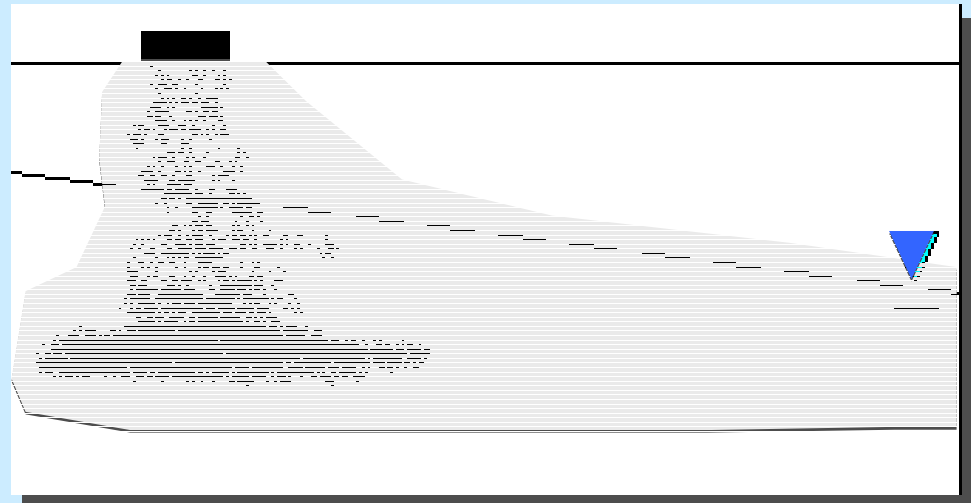
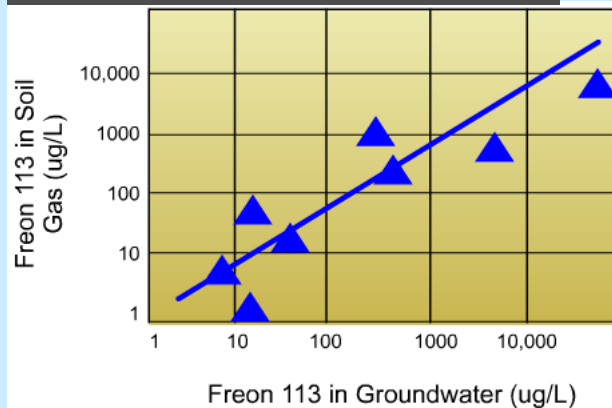


# Vertical and Bedding Plane Fractures in the Lockport Dolomite Outcrop



# Soil-Gas Surveys

- Rapid delineation of volatile organic compounds (VOCs) evolving from NAPL in the vadose zone (source areas)
- Delineate shallow GW contamination
- Less effective for deep GW contamination

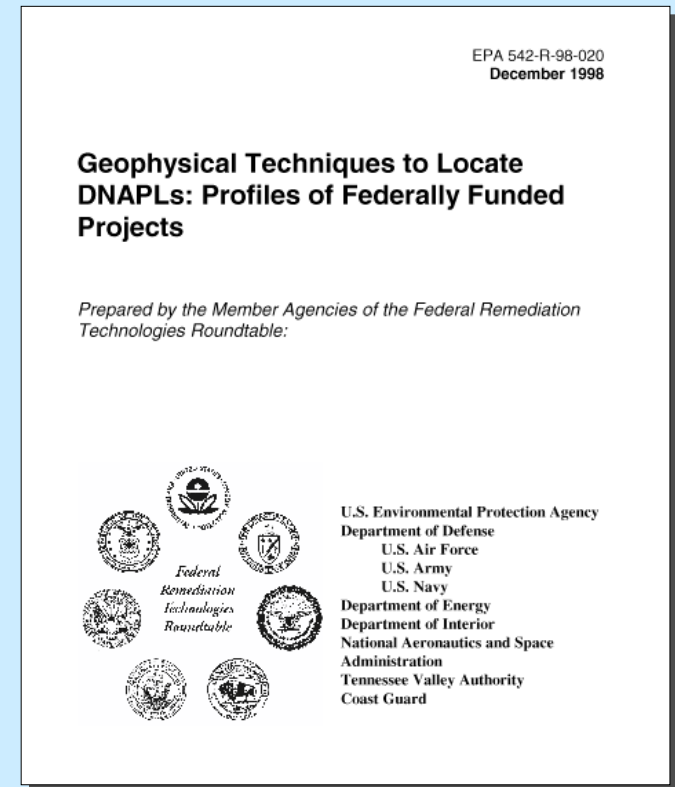


## Soil-Gas Surveys (cont.)

- Older releases in hot environments (e.g., arid West) may have limited signal due to volatilization
- Can use passive soil-gas sampling, e.g., Gore-Sorber<sup>®</sup> (cost: \$125-225/sample + equipment cost of \$25-85/day + mob cost of \$200-600/day)
- Can use active soil-gas sampling (cost: \$110-190/sample)
- Phased approach: passive, active, vertical soil-gas monitoring (LaPlante, 2002) (DoD facility)

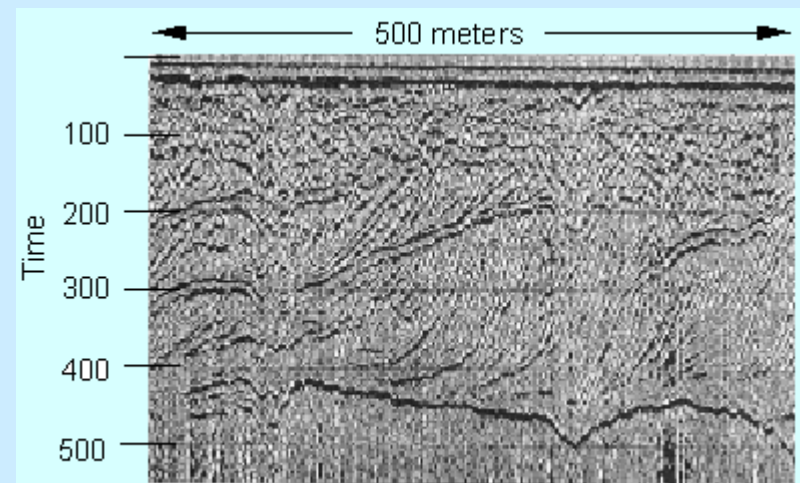
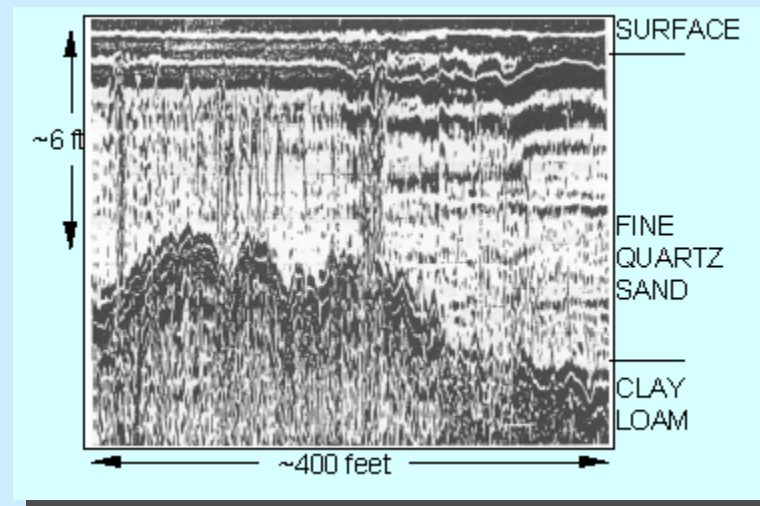
# Surface Geophysical Surveys

- Conventional surface methods to delineate stratigraphy, buried metal, and conductive fluids
- Less widely used high resolution techniques
  - To delineate DNAPL traps
  - To infer DNAPL presence
- Methods subject to numerous interferences and interpretation errors



# Ground-Penetrating Radar (GPR)

- Measures dielectric and conductivity properties by transmitting electromagnetic waves and recording their reflection
- Used to delineate stratigraphy, buried wastes, and utilities in cross section
- Penetration typically 6 to 30 feet bgs – limited by increasing clay content, fluid content, and fluid conductivity



# Electromagnetic (EM) Conductivity

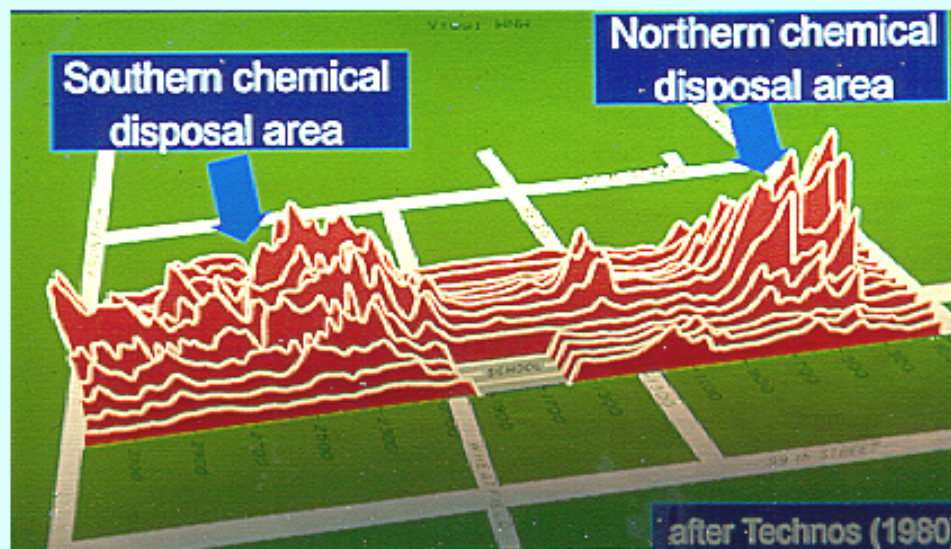
- Measures bulk electrical conductance by recording changes in induced EM currents
- Used to infer presence of conductive contaminants, buried wastes, and stratigraphy
- Station measurements, depth depends on transmitter-receiver spacing



Source: Geonics, 1999

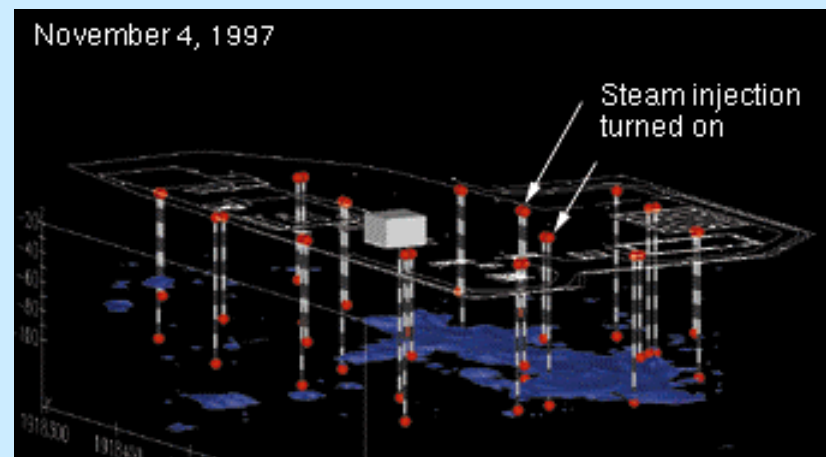


Source: Geonics, 1999



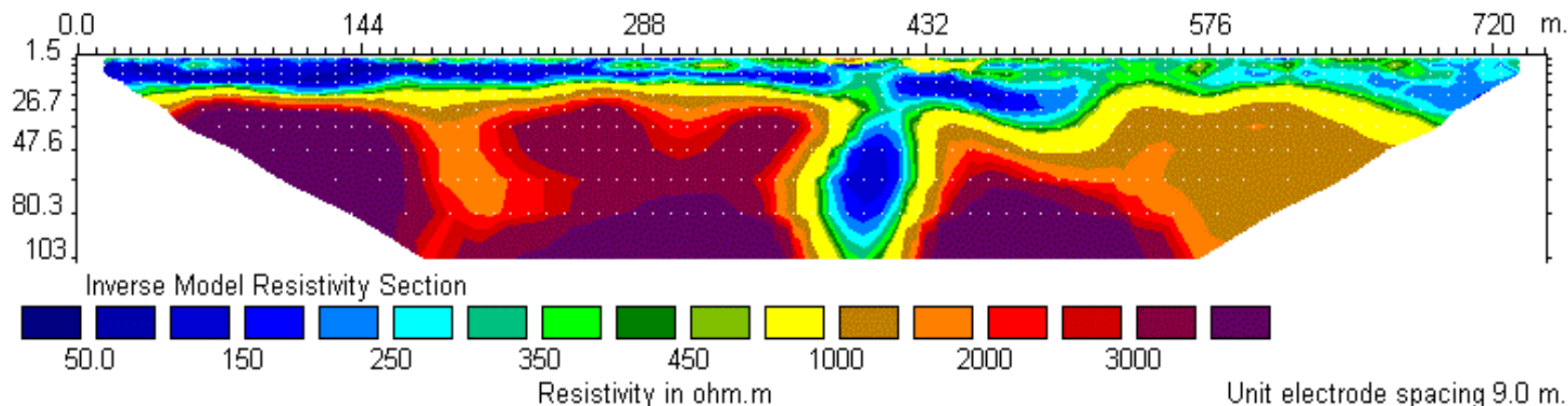
# Electrical Resistivity

- Measures resistivity of subsurface including effects of soil type (clay content), bedrock fractures, contaminants, and groundwater
- Used to delineate stratigraphy, infer depth to water table, locate fractures and faults, identify karst features, etc.
- Electric resistance tomography (ERT), using cross-hole electrode arrays



**Resistivity increases used to track steam injection at Visalia, CA wood-treating site**

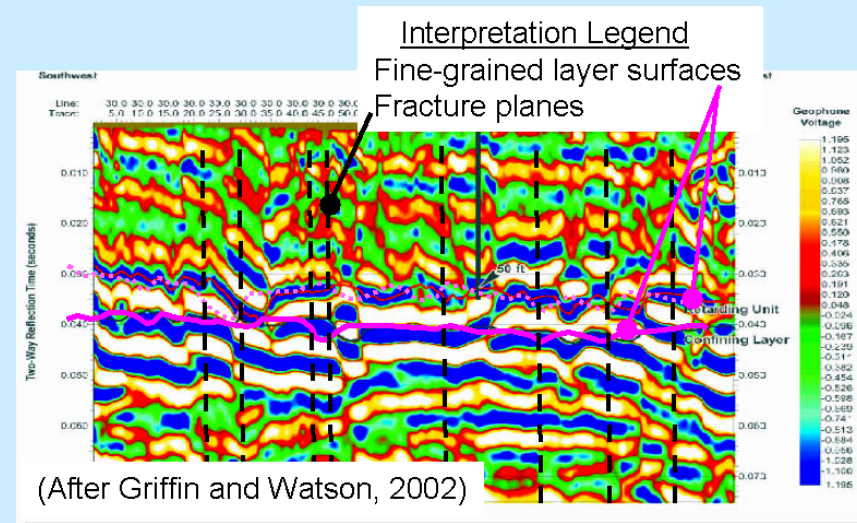
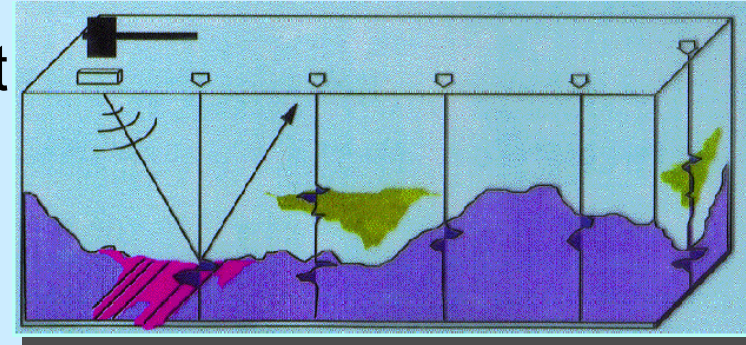
Source: SteamTech and [www.llnl.gov](http://www.llnl.gov)



# High-Resolution Seismic Reflection

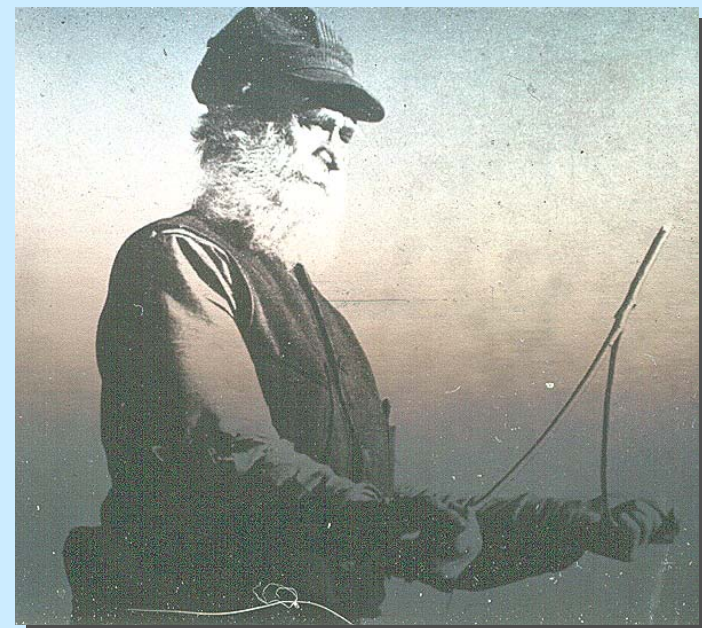
## DoD / NFESC Demonstration (DoD, 10/99)

- Evaluate 3-D seismic reflection to detect DNAPL and delineate stratigraphy
- Acoustic energy reflects off strata interfaces (and DNAPL?)
- Four test sites: Letterkenny Army Depot (PA), NAS Alameda (CA), Tinker AFB (OK), Allegany Ballistics Lab (WV)
- Confirmation sampling showed DNAPL at only **1 of 27 targets**; successful target indistinguishable from other anomalies
- 3-D seismic surveys not effective at directly detecting DNAPL; potentially useful for imaging strata



# Geophysical Methods – Limitations

- Subsurface DNAPL is a poor target for geophysical methods
- Thus, direct detection of DNAPL is unlikely
- Geophysical methods are used to delineate stratigraphy, which may assist DNAPL delineation
- Changes in DNAPL saturation have been detected using geophysical methods during research studies
- Use of geophysical methods to attempt direct detection of NAPL has mainly been limited to research projects and government funded demonstration projects



# Presentation Overview

- Definitions
- Why is DNAPL an Issue?
- Regulatory History and Status
- Strategies for Detection and Characterization

## ■ Tools for Characterization

- Noninvasive

- Invasive

- Summary

# Invasive Tools for DNAPL Characterization

- **Test Pits**
- **Probing and Drilling**
- **Soil Examination Methods**
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses

- **Downhole Methods**

- Membrane Interface Probe (MIP)
  - RNS (aka NAPL FLUTe)
  - Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

- **Groundwater Quality Profiling using Direct Push (DP) and Multilevel Wells**

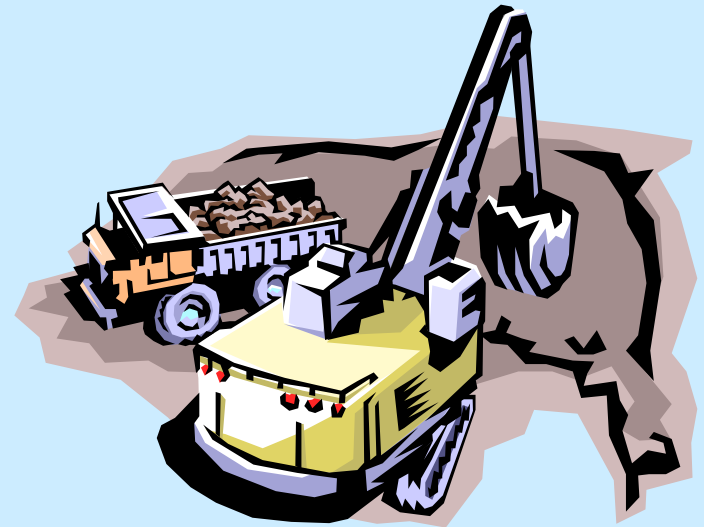
- **Well Measurements for NAPL Distribution**

- **Characterization of NAPL Samples**

- **Borehole Geophysics**

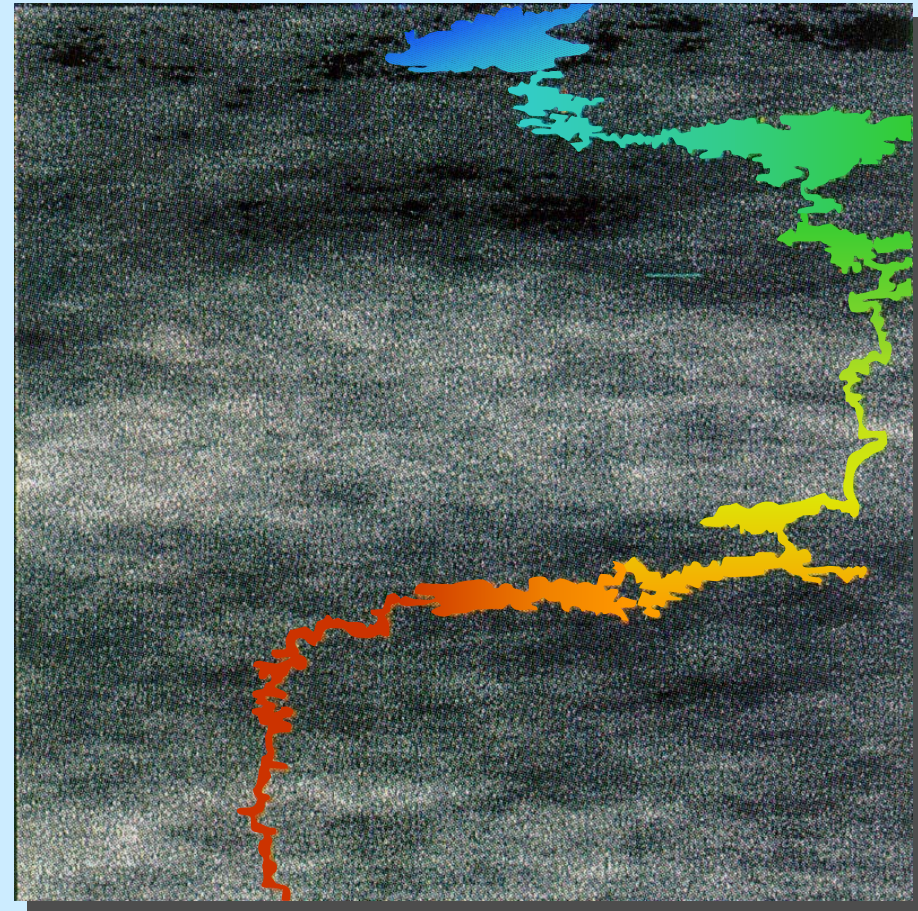
- **Partitioning Interwell Tracer Test (PITT)**

- **The Future**



# DNAPL Delineation Challenges

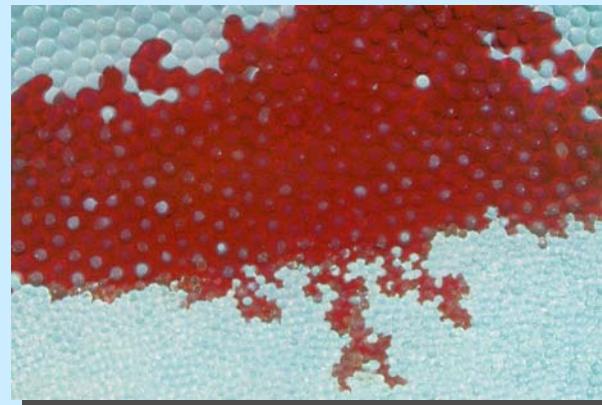
- Limited information about sources/releases
- Complex migration patterns
- Small volumes, which can create persistent dissolved plumes, are difficult to delineate  
"needle in haystack" problem
- Risk of mobilization by intrusive characterization activities



Source: Ewing, R.P. and B. Berkowitz, 1998  
Reproduced by permission of AGU

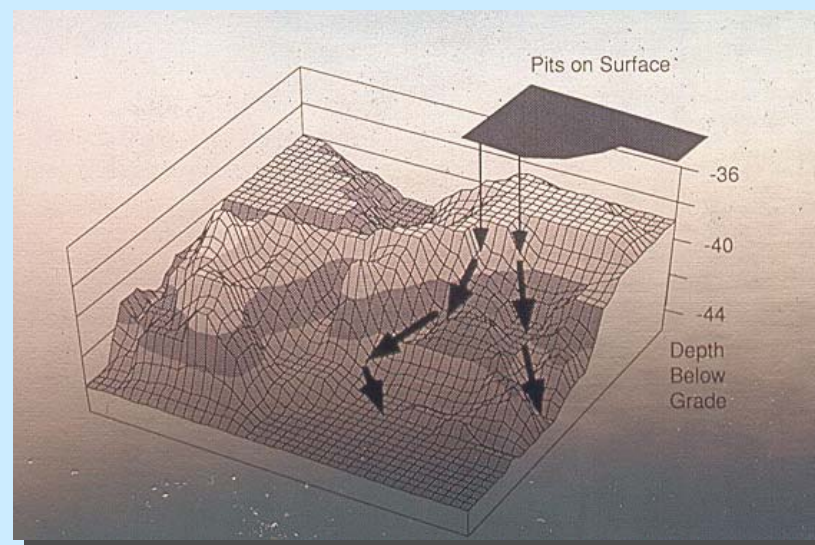
# Use Site Conceptual Model to Focus Investigation

- Effects of capillary pressure and gravity
- Stratigraphic barriers and traps
  - Is there a bottom to the site?
  - Organic layer absorbent (e.g., peat)?
- Migration pathways
  - Fractures in rock or cohesive soil
  - Coarse lenses and layers
  - Rootholes
  - Man-made structures (sewers, foundations, wells)
  - Heterogeneity and anisotropy
- Fine-grained diffusion sources



Source: Schville, 1988

Reproduced by permission of CRC Press



Source: Newell and Connor, 1992

# Invasive Characterization Method Goals

- Unambiguously identify DNAPLs in the subsurface
- Minimize investigation-derived waste (IDW)
- Eliminate undesirable gravitational movement of DNAPLs
- Provide cost savings



## ■ Test Pits

### ■ Probing and Drilling

### ■ Soil Examination Methods

- Organic vapor analysis (OVA)
- Ultraviolet (UV) fluorescence
- Hydrophobic dye shake test
- Ribbon NAPL Sampler (RNS) core strip test
- Chemical and partitioning analyses

### ■ Downhole Methods

- Membrane Interface Probe (MIP)
- RNS (aka NAPL FLUTe)
- Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

### ■ Groundwater Quality Profiling using Direct Push (DP) and Multilevel Wells

### ■ Well Measurements for NAPL Distribution

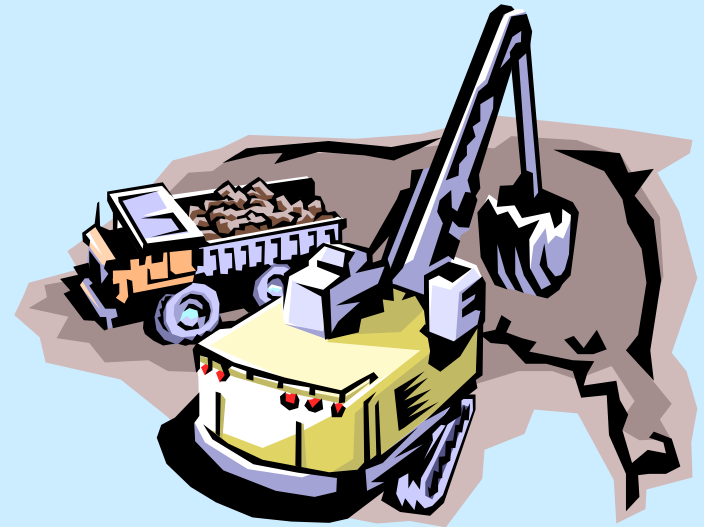
### ■ Characterization of NAPL Samples

### ■ Borehole Geophysics

### ■ Partitioning Interwell Tracer Test (PITT)

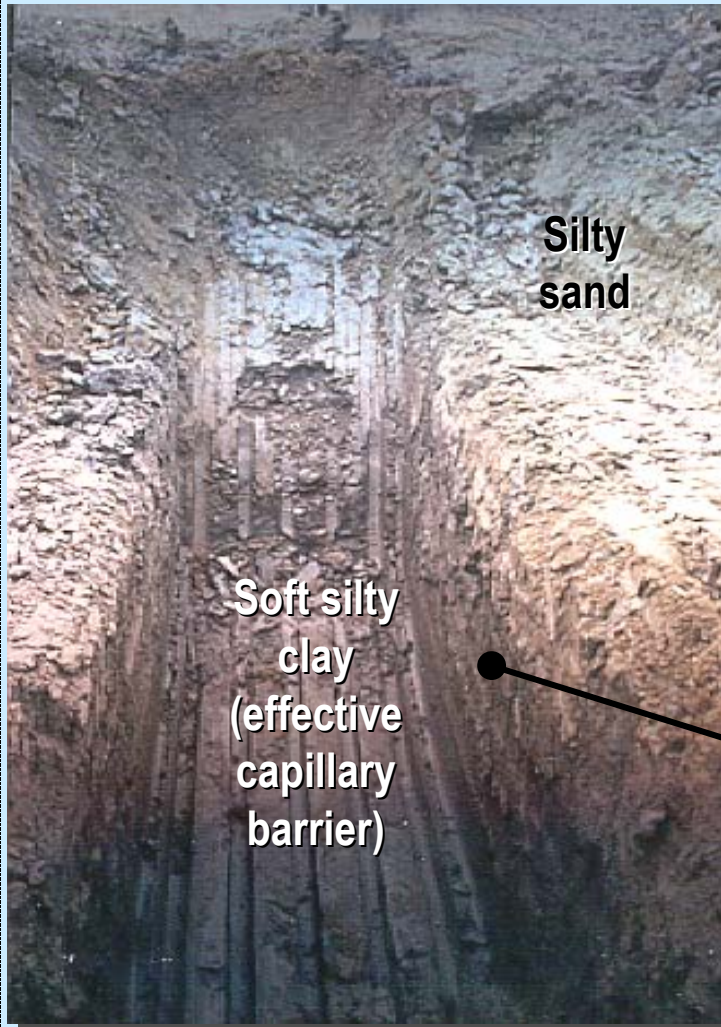
### ■ The Future

# Invasive Tools for DNAPL Characterization

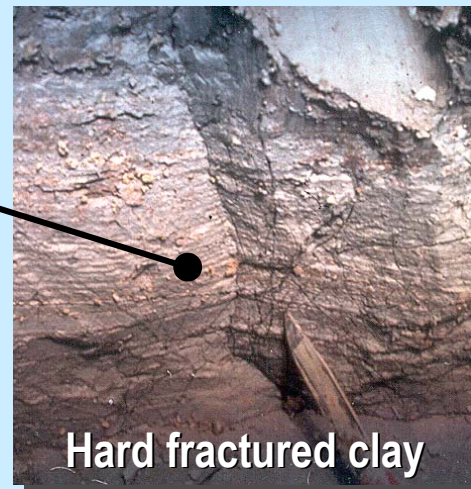


# Test Pits

- Used to define shallow soil stratigraphy, structure, and NAPL distribution



Love Canal site,  
Niagara Falls, NY



Hard fractured clay



## ■ Test Pits

## ■ Probing and Drilling

### ■ Soil Examination Methods

- Organic vapor analysis (OVA)
- Ultraviolet (UV) fluorescence
- Hydrophobic dye shake test
- Ribbon NAPL Sampler (RNS) core strip test
- Chemical and partitioning analyses

### ■ Downhole Methods

- Membrane Interface Probe (MIP)
- RNS (aka NAPL FLUTe)
- Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

### ■ Groundwater Quality Profiling using Direct Push (DP) and Multilevel Wells

### ■ Well Measurements for NAPL Distribution

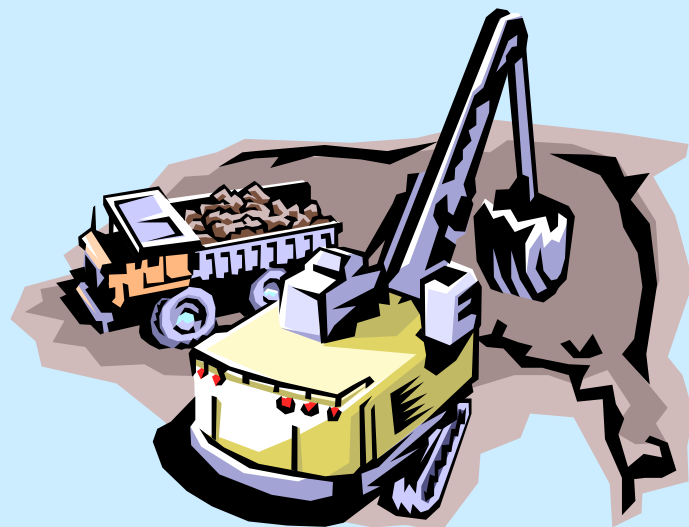
### ■ Characterization of NAPL Samples

### ■ Borehole Geophysics

### ■ Partitioning Interwell Tracer Test (PITT)

### ■ The Future

# Invasive Tools for DNAPL Characterization



# DNAPL Characterization Using Soil Cores

- Continuous cored soil samples can help identify DNAPL presence and migration pathways
- Soil coring with direct push technology (i.e., Geoprobe®) is relatively inexpensive
- Use sample tube liners to minimize VOC losses
- A photoionization detector (PID) can be used to select "hot" portions of the soil core for sampling and preservation
- Perform soil sampling of suspected source areas using methanol as a preservative (EPA SW846 Method 5035)

# Benefits of Direct-Push Sampling

## Rotary Hammer (Percussion) and Cone Penetration Units


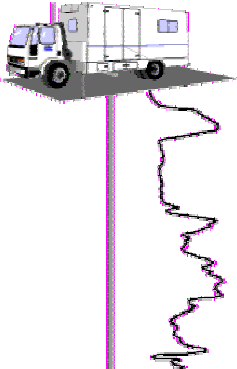
- Rapid stratigraphic logging and contaminant detection using sensor systems
- Rapid, depth-discrete sampling of soil, soil gas, and water
- No drill cuttings, little IDW
- Minimally invasive; effective grouting and sealing capabilities
- Reduced potential for contaminant drag-down
- Standard methods
  - Direct-push soil sampling (ASTM D-6282)
  - Direct-push groundwater sampling (ASTM D-6001)
  - Cone penetration testing (ASTM D-3441)

# Geoprobe® and Cone Penetration Tools

- Soil gas sampler
- Soil sampler
- Groundwater sampler
- CPT – stratigraphy
- Soil moisture probe
- Electrical conductivity/resistivity
- Fluorescence detector
- Downhole camera
- MIP and thermal desorption VOC sampler
- Permeability
- Grouting module

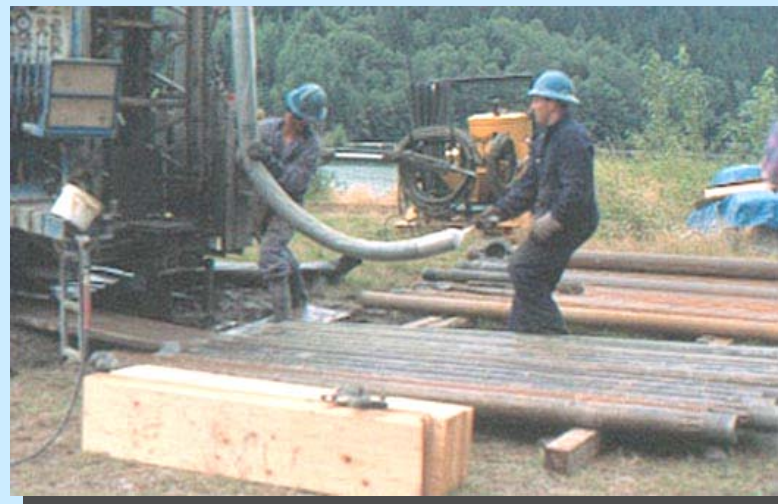


# Comparison of Direct Push Methods

Technique	Advantage	Limitation
<p>Percussion Probing (Geoprobe®)</p> 	<ul style="list-style-type: none"> <li>■ Less expensive</li> <li>■ More mobile and available</li> <li>■ Well-developed sampling tools</li> <li>■ Availability of certain sensors</li> </ul>	<ul style="list-style-type: none"> <li>■ Difficult to penetrate hard/dense soils</li> <li>■ Depth limitation</li> </ul>
<p>Cone Penetration</p> 	<ul style="list-style-type: none"> <li>■ Greater depth penetration</li> <li>■ Certain sensors better developed (LIF, tip resistance, sleeve friction, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>■ More expensive</li> <li>■ Less available</li> <li>■ Less maneuverable</li> </ul>

# Rotasonic Drilling

- Employs use of high-frequency mechanical vibration and limited rotary power to drill
- Can provide excellent quality, large diameter, relatively undisturbed core of soil and rock for characterization
- Maximizes core volume, minimizes other IDW
- Contaminant drag-down a concern; (reduce risk by drilling through isolation casing)
- Fast
- Limited availability and high cost



Photos courtesy of Sonic Drill Corp.

# Drilling at DNAPL Sites



## DNAPL on Lockport Dolomite

Hyde Park Landfill Site,  
Niagara Falls, NY

- All methods present some risk of drag-down and mobilization
- Many precautions can be taken to limit risk
  - Outside-in
  - Carefully examine samples and screening data
  - Telescope
  - Use direct push
  - Control hydraulic pressure in hole
  - Minimize open-hole length and duration
  - Stay shallow, monitor deep downgradient

## ■ Test Pits

## ■ Probing and Drilling

## ■ Soil Examination Methods

- Organic vapor analysis (OVA)
- Ultraviolet (UV) fluorescence
- Hydrophobic dye shake test
- Ribbon NAPL Sampler (RNS) core strip test
- Chemical and partitioning analyses

## ■ Downhole Methods

- Membrane Interface Probe (MIP)
- RNS (aka NAPL FLUTe)
- Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

## ■ Groundwater Quality Profiling using Direct Push (DP) and Multilevel Wells

## ■ Well Measurements for NAPL Distribution

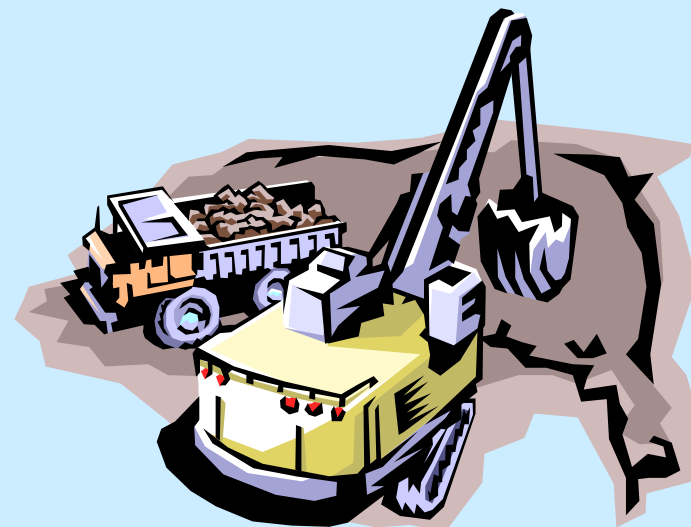
## ■ Characterization of NAPL Samples

## ■ Borehole Geophysics

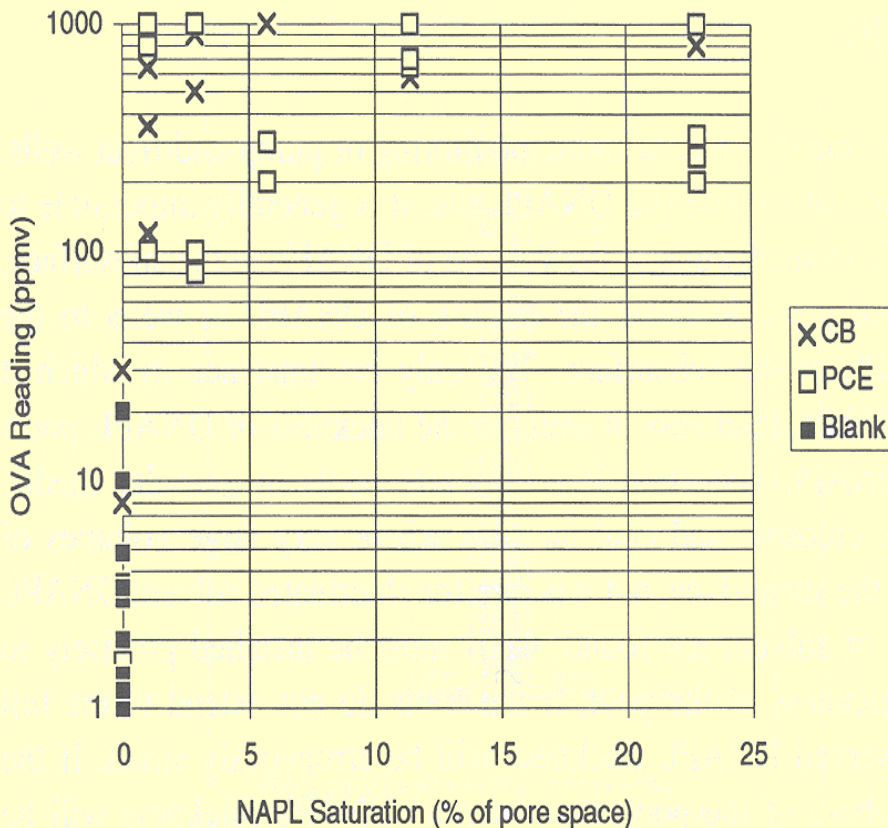
## ■ Partitioning Interwell Tracer Test (PITT)

## ■ The Future

# Invasive Tools for DNAPL Characterization



# Organic Vapor Analysis Screening of Soil Cores



## Sample headspace experiment results

Source: Cohen et al., 1992

- Rapid and inexpensive
- High concentrations of VOCs associated with NAPL presence
- Useful to focus sampling
- Readings sensitive to effective contaminant volatility, water content, sample temperature, and sample handling



## OVA screening of soil core

Source: Griffin and Watson, 2002b

# UV Fluorescence

- Common chlorinated solvents generally **do not fluoresce** unless mixed with fluorescent impurities:
  - Oil and grease removed by solvent in degreasing operations
  - Petroleum products encountered in the subsurface
  - Humic compounds from natural organic matter
- Coal tar and creosote DNAPLs fluoresce
- Naturally occurring fluorophores (e.g., calcium carbonate shell fragments in coastal plain sediments) can confound use of fluorescence as a contaminant detection tool



Coal tar fluorescence  
in soil core

# UV Fluorescence Detection Methods

## Advantages

- Quick and inexpensive
- Many NAPLs fluoresce
- Can provide detailed information on relationship between stratigraphy and contaminant distribution
- Can document using a digital camera

## Limitations

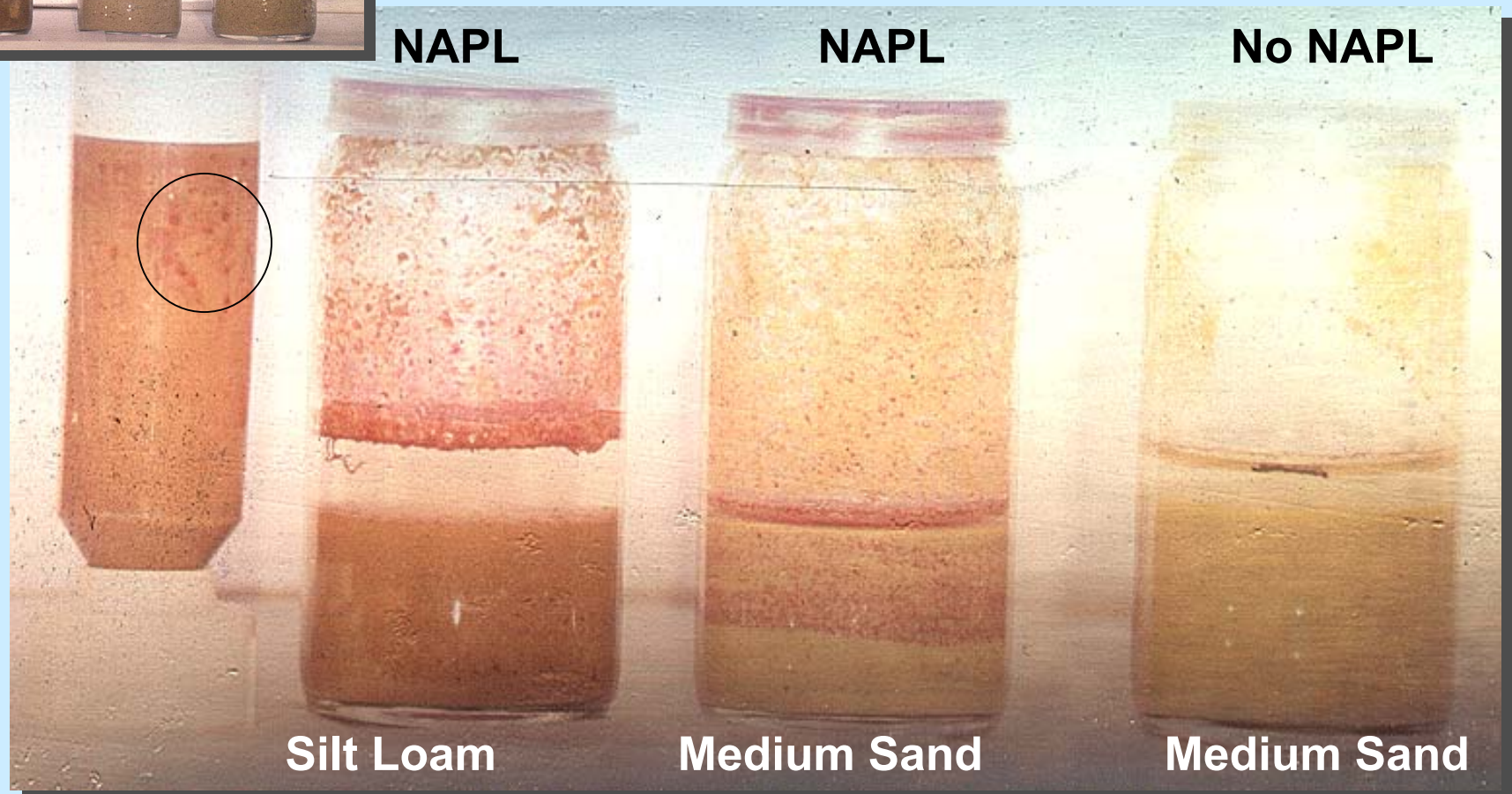
- Requires fluorescent NAPL
- Indiscriminate
- Interference from non-target fluorescent materials (such as shell fragments in coastal sediment)
- Significant potential for false positives and false negatives

Known background and NAPL-contaminated samples should be checked for interference and site-specific NAPL response

# Hydrophobic Dye Shake Test



Mix soil sample with water and a tiny amount of hydrophobic dye powder (e.g., Sudan IV)



# Hydrophobic Dye Shake Test

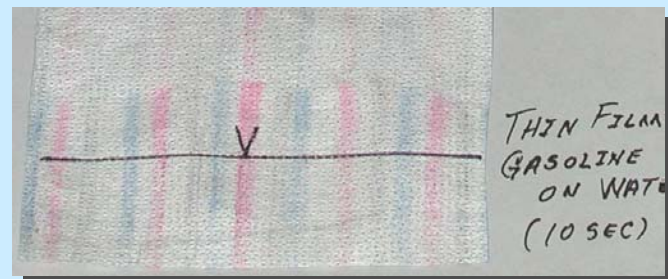
## Use and Limitations

- Known background and NAPL-contaminated samples should be examined to check for interference and site-specific response
- Can only detect NAPL if present in sample
- Potential for false positives (reaction with other organic matter) and false negatives (not enough NAPL present)
- Visual contrast can be difficult to discern in dark soil

## Using a Ribbon NAPL Sampler (RNS) (aka NAPL FLUTe™) to Detect NAPL in Soil Core

- The RNS, developed for downhole emplacement, can be used to find NAPL in rotasonic drill soil core samples
- The RNS cover is a **hydrophobic dye-striped** tubular fabric designed to contact soil core extruded from a barrel
- NAPL that contacts the RNS will react with its dye and produce a visible stain on the outside of the cover
- The core bag can be photographed, manipulated to increase soil contact with the reactive fabric, and slit open for vapor analysis and sampling

Source: [www.flut.com](http://www.flut.com)



RNS tubular cover is pulled from reel, cut, inverted, and knotted.



A

RNS cover is slipped over the core barrel.



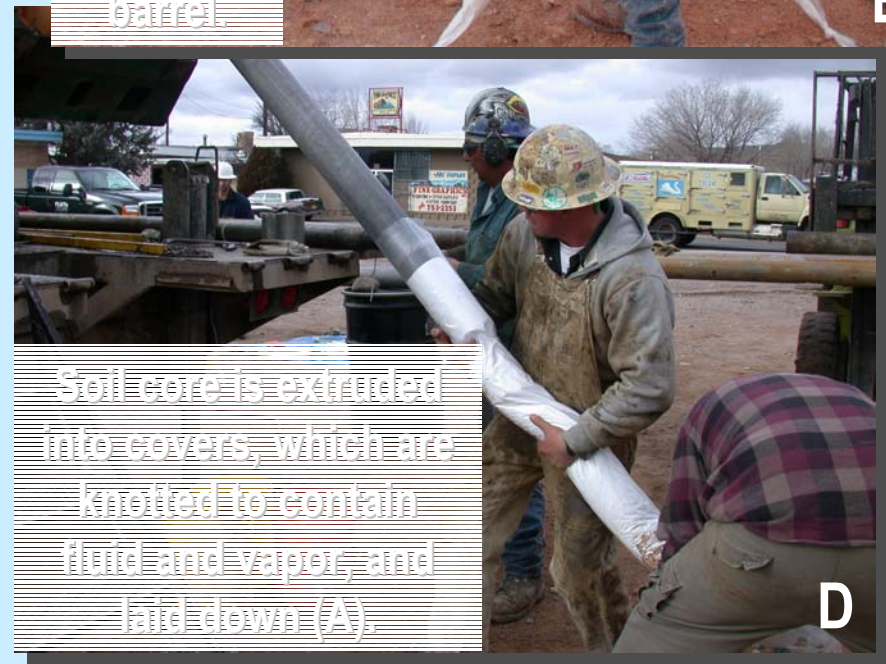
B

The basic tubular plastic core cover is slipped over RNS cover.



C

Soil core is extruded into covers, which are knotted to contain fluid and vapor, and laid down (A).



D

## Example Results Using Dye Strips

SB-6 at 45.5 ft bgs

Visual: ND

UV: ND

Dye Shake Test: ND

OVA: 3,000 ppm

Analysis: 0.065 mg/kg Freon 113

SB-14 at 54 ft bgs

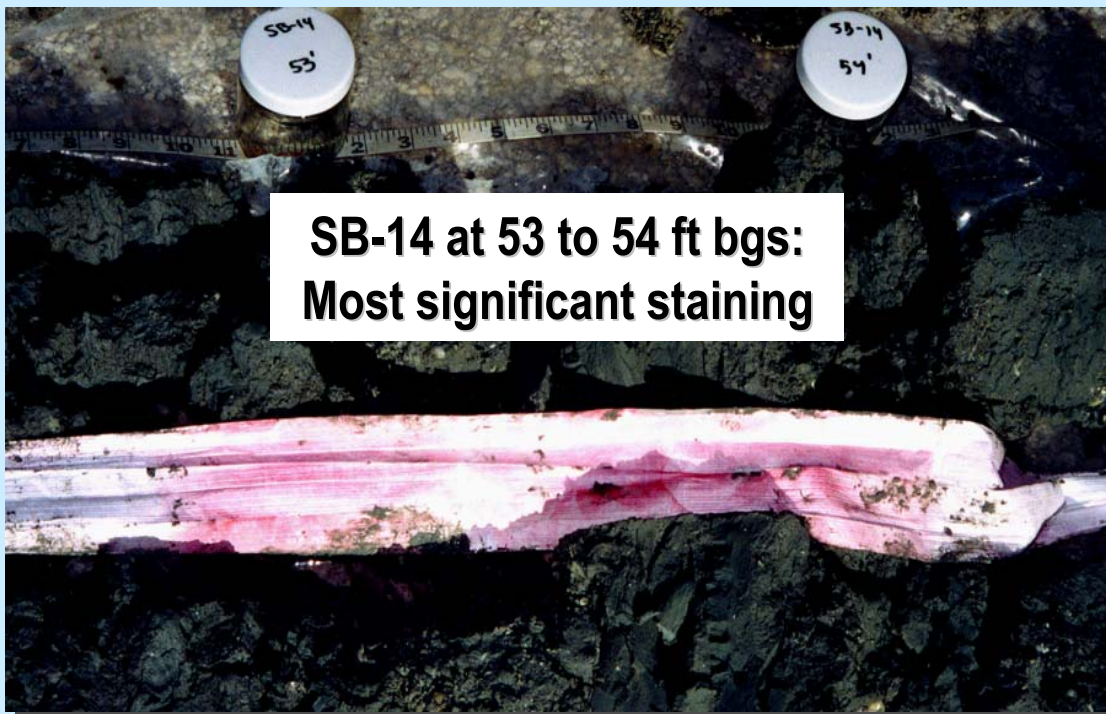
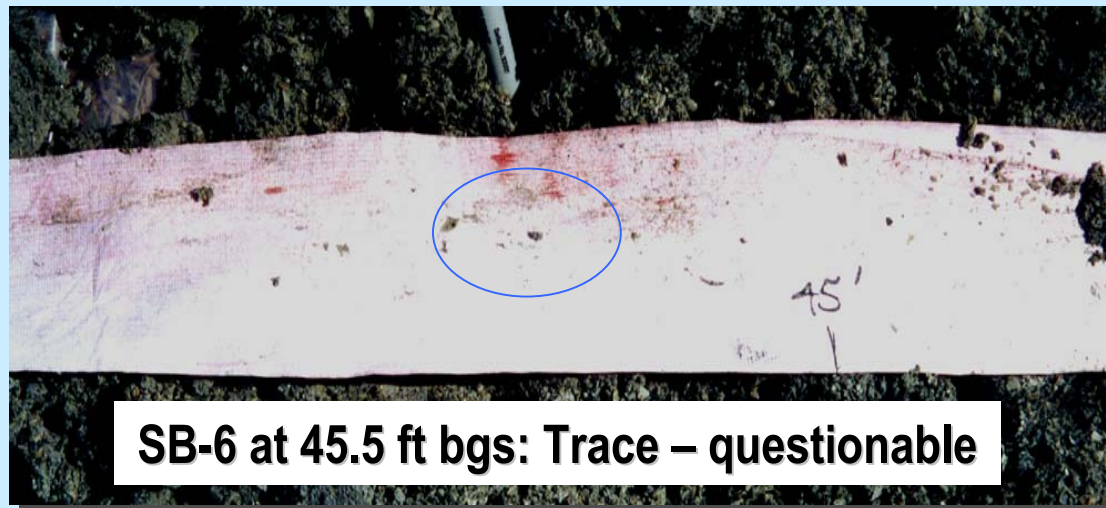
Visual: ND

UV: ND

Dye Shake Test: ND

OVA: >5,000 ppm

Analysis: 680 mg/kg Freon 113



Note: Freon 113 concentration >84 mg/kg suggests NAPL presence

# Using RNS Strips to Detect NAPL in Soil Core

## Advantages

- Relatively simple, direct, and cost-effective (~\$4/ft for hydrophobic dye-impregnated cover)
- Can provide detailed information on relationship between stratigraphy and contaminant distribution
- Amenable to rapid documentation via photography

## Limitations

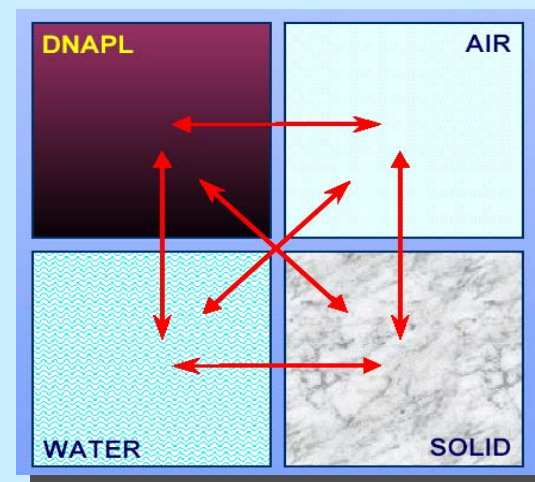
- Minor discoloration of liner associated with handling and contact with plastic core sleeves
- Relatively faint reaction to some NAPLs
- Color fading and/or non-detection due to evaporation
- Wicking may exaggerate NAPL presence
- Potential for false positives and false negatives

# Chemical Analysis of Soil Core Samples

- Collect the soil sample with preservation
- Analyze the extract (preservative) and back-calculate soil concentrations
- Use soil concentrations to determine the DNAPL saturation in the soil and more

# Calculating DNAPL Saturation in Soil Based on Chemical Analysis and Equilibrium Partitioning Calculation

- Feenstra et al. (1991)
  - Assesses presence of NAPL
- Mott (1995): SOILCALC
  - Assesses presence of NAPL
  - Estimates NAPL composition
- Mariner et al. (1997): NAPLANAL calculates:
  - NAPL saturation
  - NAPL composition
  - VOC concentrations in each phase
  - NAPL composition and volume in water-NAPL emulsions ( $\chi_s = 0$ )
  - NAPLANAL available at [www.dnapl.com/publications.html](http://www.dnapl.com/publications.html)



Mass of  $i$  = sum of mass of  $i$  in all phases:

$$\rho_t C_t^i = \phi_w C_w^i + \phi_a C_a^i + \phi_n C_n^i + \phi_s C_s^i$$

Total density = weighted average of all densities:

$$\rho_t = \phi_w \rho_w + \phi_a \rho_a + \phi_n \rho_n + \phi_s \rho_s$$

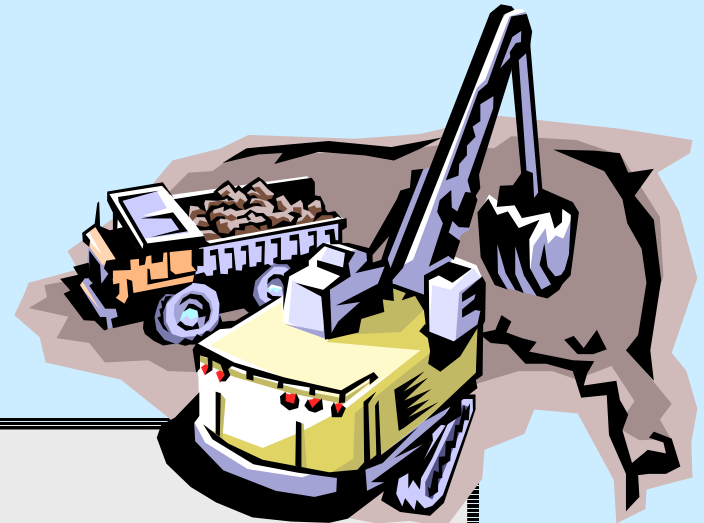
Source: Duke Engineering and Services, 1998

# Invasive Tools for DNAPL Characterization

- Test Pits
- Probing and Drilling
- Soil Examination Methods
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses

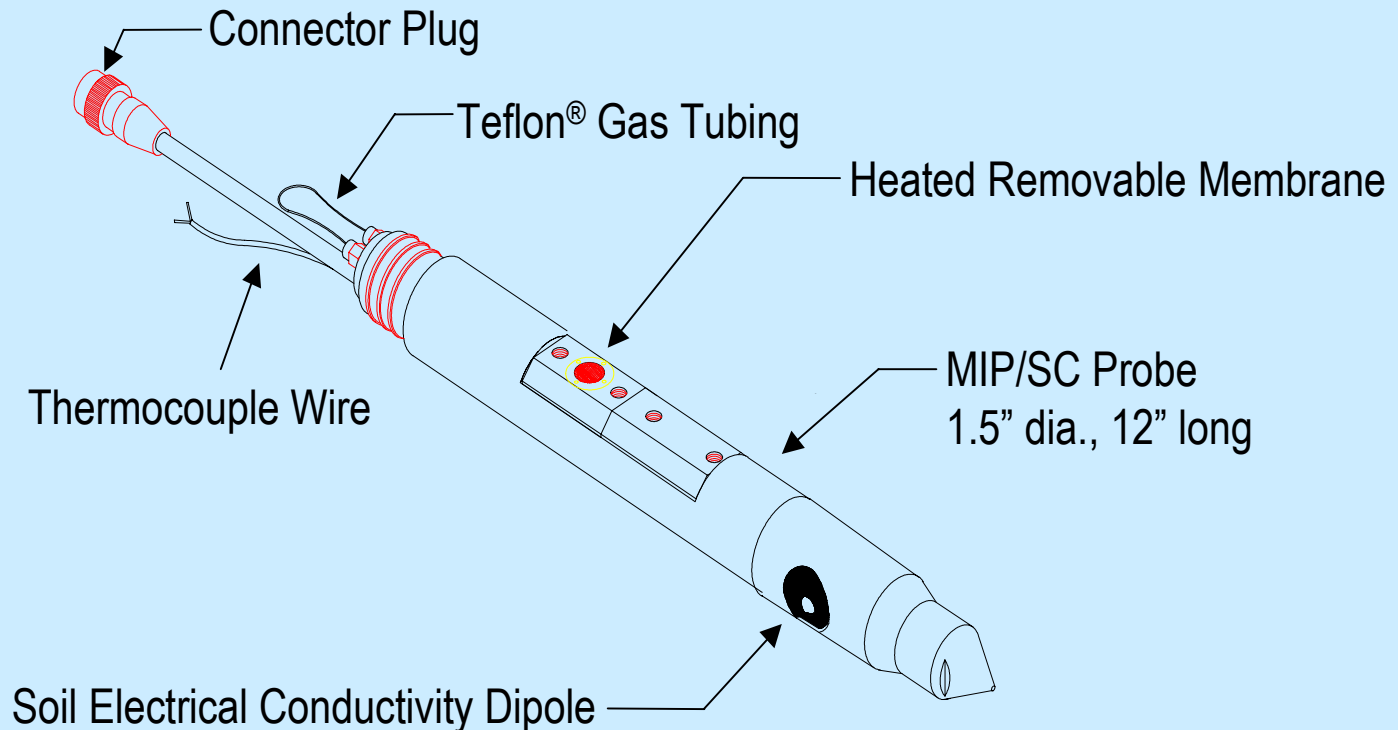
## ■ Downhole Methods

- Membrane Interface Probe (MIP)
- RNS (aka NAPL FLUTe)
- Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)
- Groundwater Quality Profiling using Direct Push (DP) and Multilevel Wells
- Well Measurements for NAPL Distribution
- Characterization of NAPL Samples
- Borehole Geophysics
- Partitioning Interwell Tracer Test (PITT)
- The Future

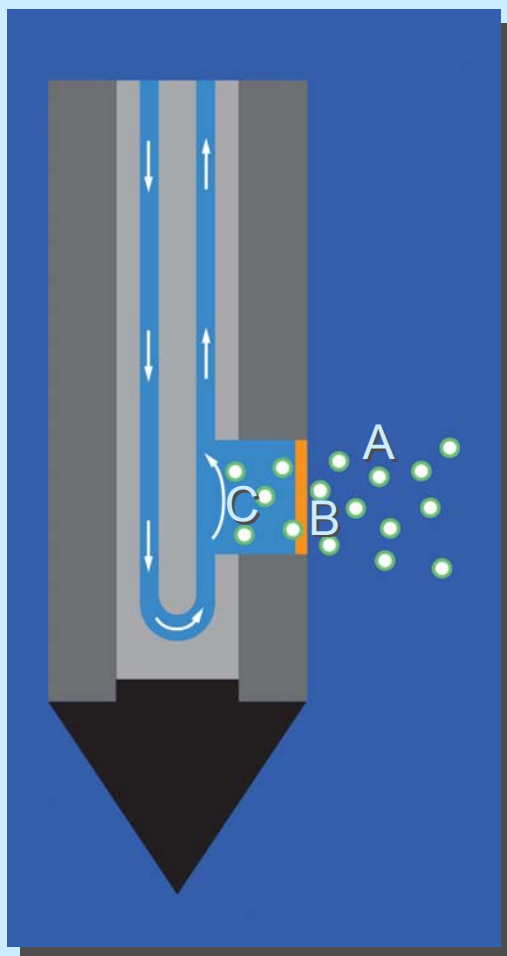


# Geoprobe® Membrane Interface Probe (MIP) and Soil Conductivity (SC) System

- A direct-push logging tool that records continuous relative VOC concentrations (MIP sensor) and electrical conductivity (SC sensor) with depth in soil. Provides rapid, real-time, detailed characterization of stratigraphy and VOC contamination.



# MIP Theory of Operation



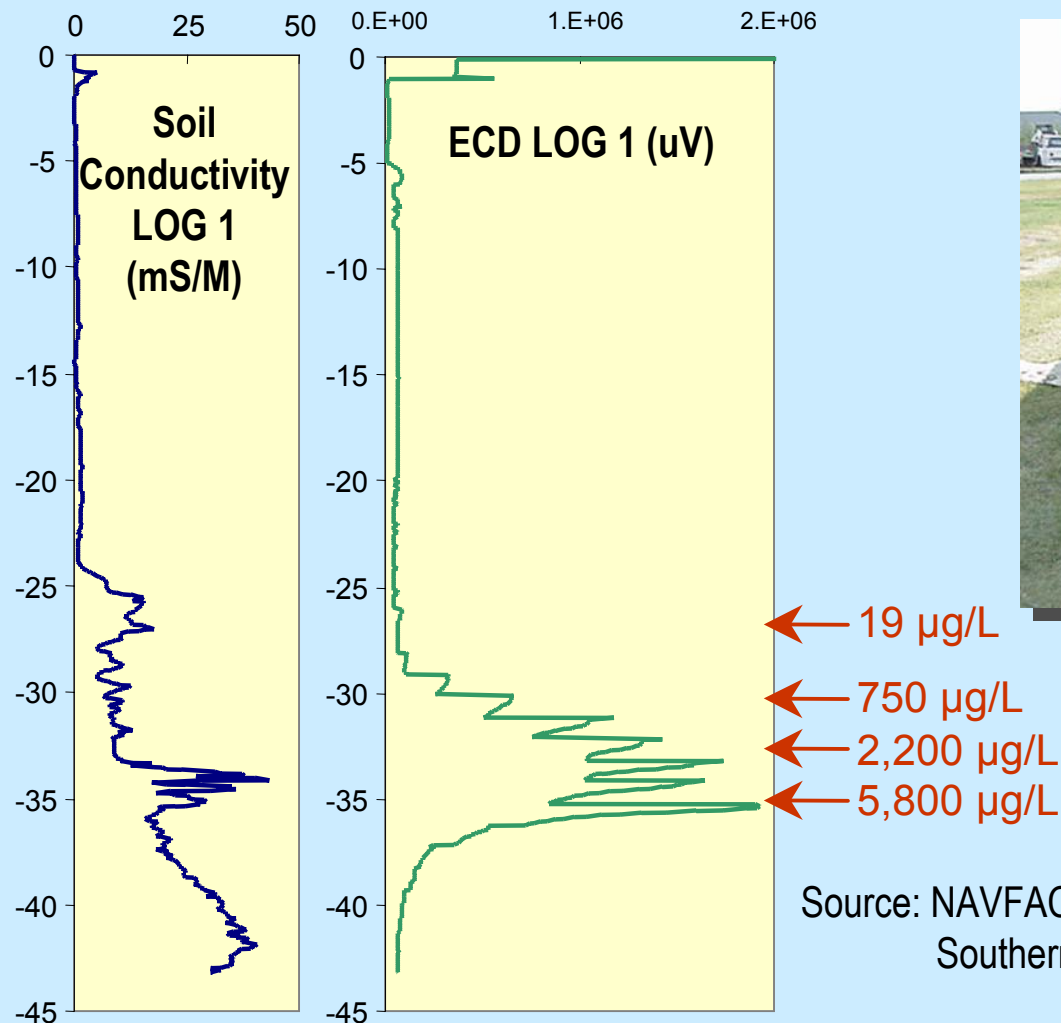
- VOCs in subsurface region (A) come into contact with a thin film Teflon<sup>®</sup> membrane (B) set in a heating block, which is heated to 120°C.
- Chemicals are volatilized and diffuse across the membrane where they are swept by an inert carrier gas (C) to various detectors at the surface.
- Continuous voltage output from VOC detectors (ECD, PID, FID) are recorded versus depth.
- Bulk fluids do not travel across the membrane; thus the MIP can be used above or below the water table.

## The MIP is for VOCs

- Provides record of output voltage of the detector connected to the gas stream:
  - An electron capture detector (ECD) for chlorinated solvents
  - A photo-ionization detector (PID) for aromatic hydrocarbons
  - A flame-ionization detector (FID) for methane and petroleum hydrocarbons
- Gas samples can be analyzed by GC/MS; water and soil sampling can be guided using MIP data
- Given its relatively high detection limits, a good use of the MIP is to help delineate DNAPL zones

# Comparing MIP and Mobile Lab GCMS Data

## Charleston Naval Complex



Source: Geoprobe® Systems

Source: NAVFAC Engineering Division  
Southern Command, 2001

**Vertical Profile of TCE via Onsite GC/MS**

# Membrane Interface Probe (MIP)

## Advantages

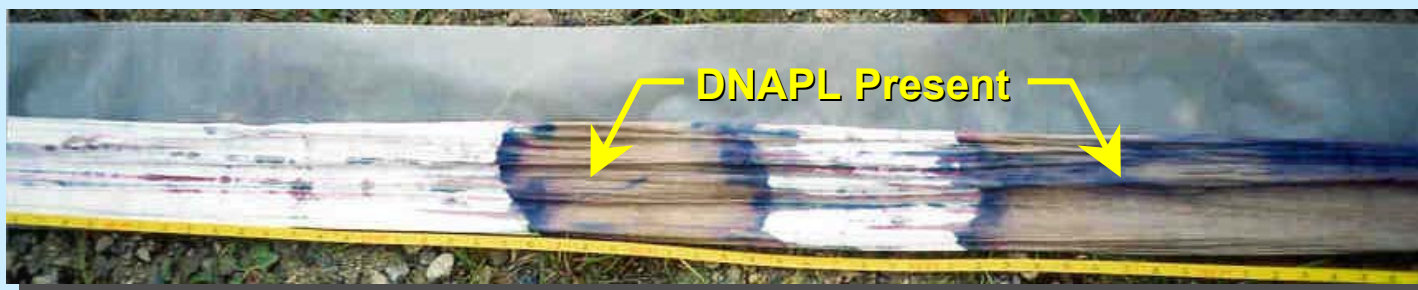
- Widely available
- Simultaneous log of VOCs and soil conductivity
- Operates in vadose zone and saturated zones
- Useful for delineating NAPL source zones
- Rapid site screening (100s of feet per day)
- Cost savings

## Limitations

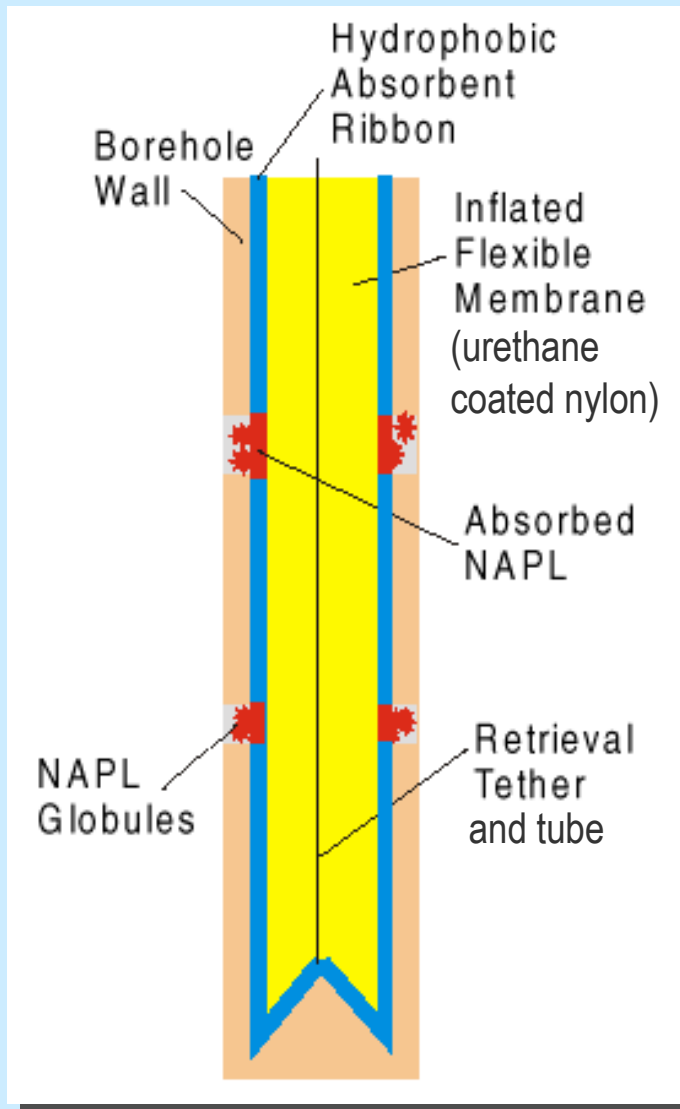
- High detection limits, qualitative analytical data
- Designed for volatile contaminants
- Contaminant carryover can be high
- Penetration resistance limitations

# Ribbon NAPL Sampler (RNS) aka NAPL FLUTe™

- A continuous, direct sampling method that can provide depth-discrete mapping of NAPL developed circa 1998 by Westinghouse Savannah River Co. and Flexible Liner Underground Technologies Ltd (FLUTe)
- Uses a pressurized flexible liner to support and seal a hole and force a dye-striped NAPL absorbent ribbon against a borehole wall
- More than 300 installations in ~30 states

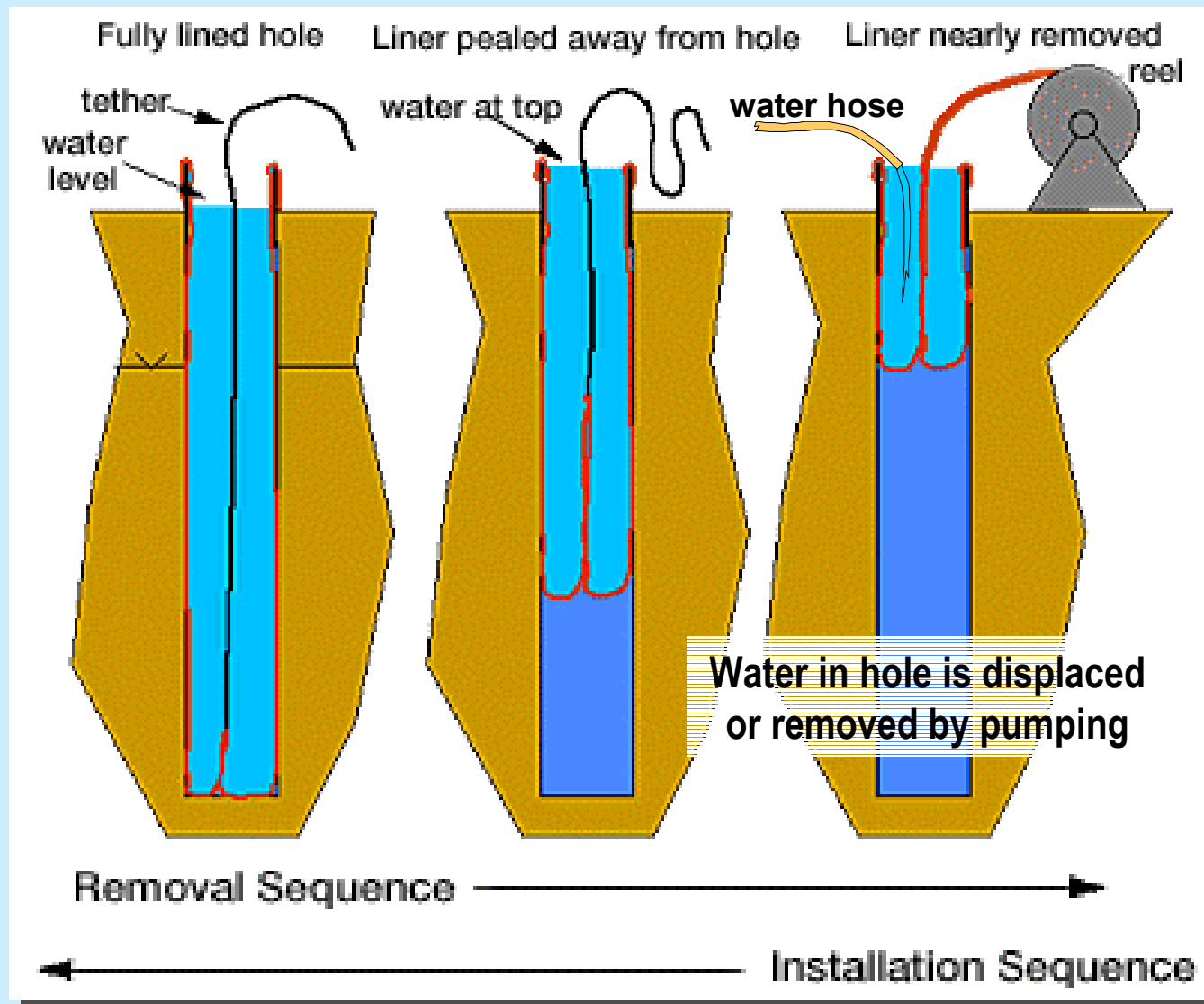


# RNS Theory of Operation



- A flexible membrane with a color-reactive hydrophobic cover is installed downhole
- NAPL wicks into the cover, leaches dye from its surface, and visibly stains the white backside of the reactive material
- The liner/cover is inverted out of the hole to prevent cross contamination of the cover
- The liner is stripped from the cover to inspect the white side of the cover for stain patterns

# RNS Emplacement by Eversion (inside-out) in Open Hole below Water Table “like taking a sock off”



# Downhole RNS (aka NAPL FLUTe™)

## Advantages

- Provides continuous record of NAPL distribution with depth at borehole location
- Can be deployed in variety of hole types
- Can provide cost savings

## Limitations

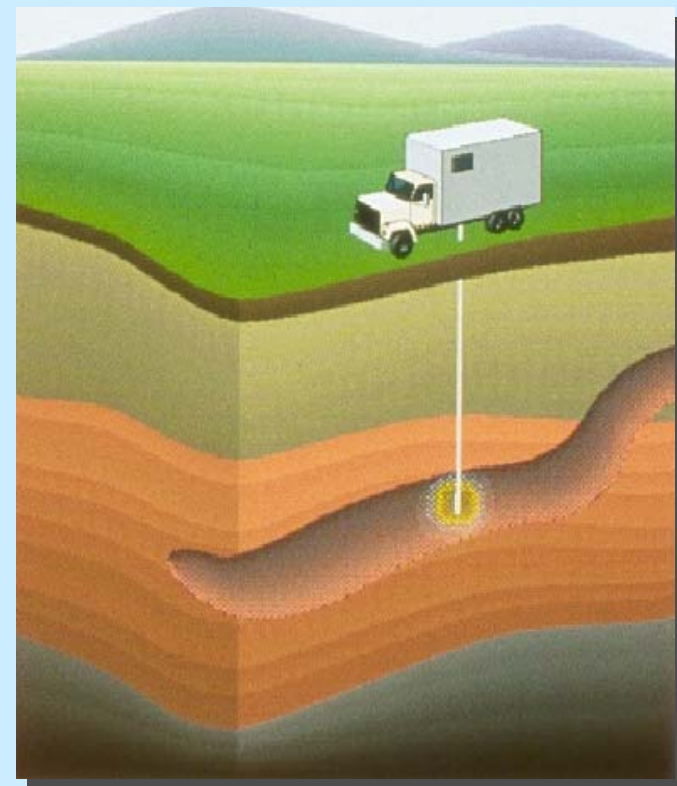
- Heterogeneity may limit value of information
- Relatively ambiguous reaction to some NAPLs may be difficult to interpret
- Wicking may exaggerate NAPL presence
- Potential for false positives and false negatives
- Potential for cross contamination

# Downhole UV Fluorescence Probes Developed in 1990s

- Site Characterization and Analysis Cone Penetrometer System (SCAPS)
  - Developed by Navy, Army, Air Force, and DOE
  - ~8 SCAPS CPT-LIF units for federal government use
- Rapid Optical Screening Tool (ROST) CPT-LIF
  - Developed by Dakota Technologies, Inc. (DTI) and marketed by Fugro Geosciences, Inc. and DTI
  - Fugro operates 7 ROST systems in U.S. and Europe
  - DTI operates 1 Geoprobe® ROST unit
- The Fuel Fluorescence Detector (FFD), with a downhole mercury lamp
  - Developed and marketed by Applied Research Associates (ARA)
  - >20 FFD units operated by various companies in U.S.

# Cone Penetrometer Technology/ Laser Induced Fluorescence (CPT/LIF)

- CPT uses strain gauges to measure soil behavior properties (tip and sleeve resistance) to provide real-time, in situ stratigraphic identification
- LIF provides real-time logging of fluorescent contaminants
- Probe continuously advanced smoothly at ~4 ft/min in accord with ASTM Standard D-3441
- CPT rigs vary from 20 to >35 tons in truck and ATV format



Source: Fugro, 1999

## LIF/FFD Applications

- Polycyclic aromatic hydrocarbons (PAHs) in petroleum products, coal tar, and creosote
- Double-ring (naphthalene) and single-ring aromatic hydrocarbons (BTEX compounds) at lower excitation wavelengths
- Chlorinated solvents (e.g., PCE, TCE) and other NAPLs mixed with fluorescent impurities can produce strong fluorescent signals
- LIF has mainly been used to delineate petroleum (at POL sites) and coal tar contamination (at wood-treating and manufactured gas plant [MGP] sites) at relatively shallow depths

# CPT/LIF UV Fluorescence Probes

## Advantages

- Real-time delineation of stratigraphy and fluorescent contamination
- Typical daily productivity of 300 to 400 feet at 10 to 15 locations
- LIF waveforms offer product identification/verification and rejection of non-contaminant fluorescence
- Reduced IDW and exposure to site contaminants
- Potential cost savings

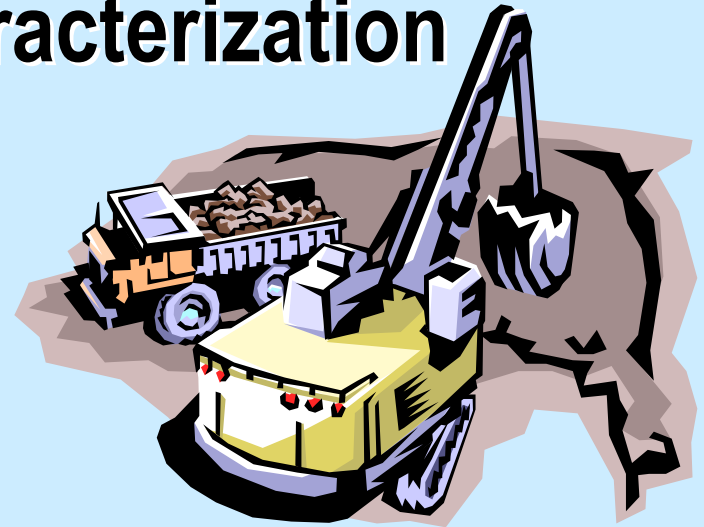
## Limitations

- Primarily applicable to PAHs
- Subject to interferences
- NAPL has to be adjacent to sapphire window
- Limited availability
- Cost



# Invasive Tools for DNAPL Characterization

- Test Pits
- Probing and Drilling
- Soil Examination Methods
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses
- Downhole Methods
  - Membrane Interface Probe (MIP)
  - RNS (aka NAPL FLUTe)
  - Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)



## ■ Groundwater Quality Profiling Using Direct Push (DP) and Multilevel Wells

- Well Measurements for NAPL Distribution
- Characterization of NAPL Samples
- Borehole Geophysics
- Partitioning Interwell Tracer Test (PITT)
- The Future

# Groundwater Quality Profiling Using DP Tools

- Collect multiple discrete groundwater samples from coarse sediments at multiple depths in a single hole
  - Waterloo Profiler®
  - Geoprobe® Dual Tube and GW Profilers
  - VERTEK ConeSipper™
- Need to know stratigraphy to select sampling zones
  - Based on CPT log, electrical conductivity (EC) log, K-test, geologic log...
- Combine with mobile lab for real-time measurement and dynamic site characterization

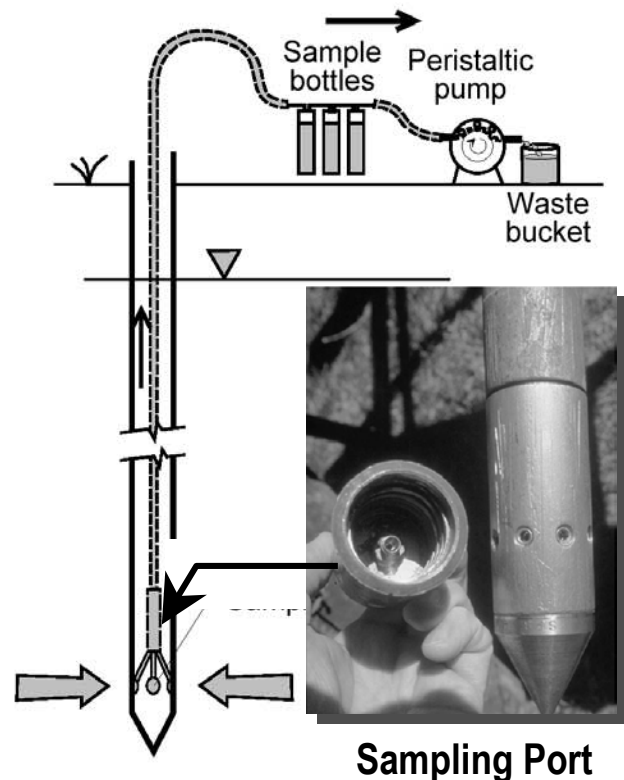


Geoprobe®  
DT21 Profiler



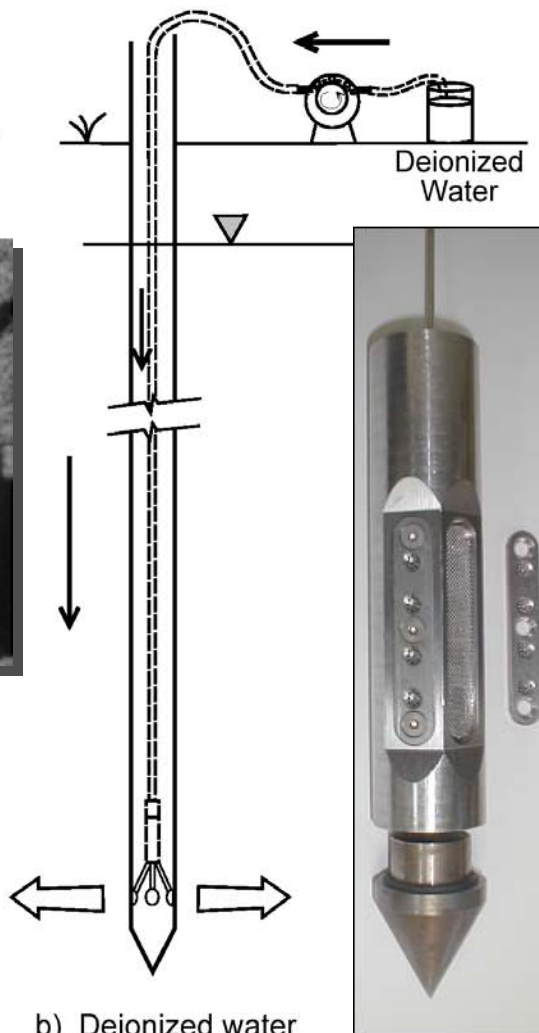
Source: Stone Environmental, Inc.

# Invasive Tools: Groundwater Quality Profiling Using DP and Multilevel Wells

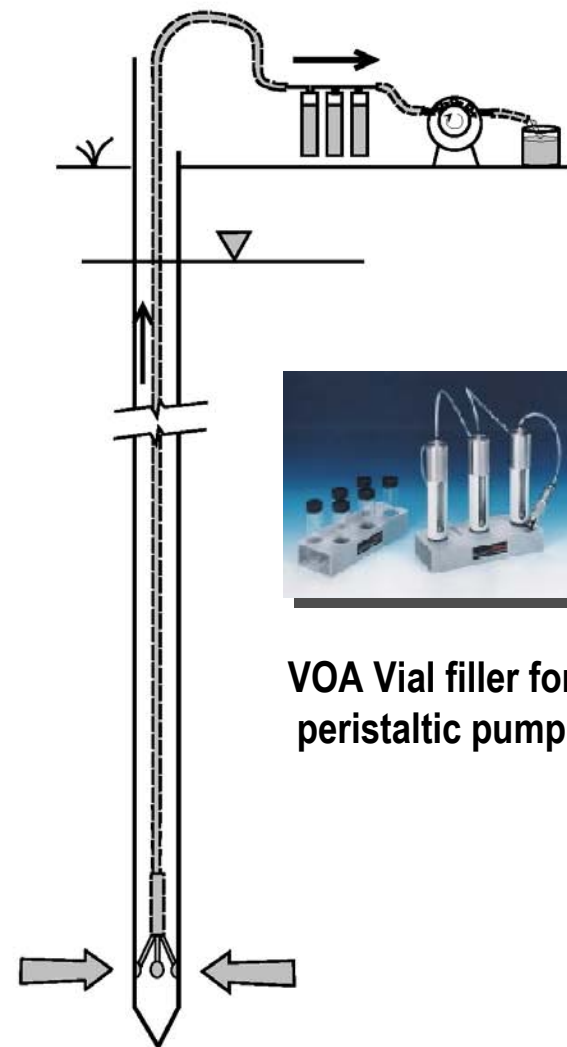


a) Groundwater sample collected from first target zone with peristaltic pump.

## Waterloo Profiler®

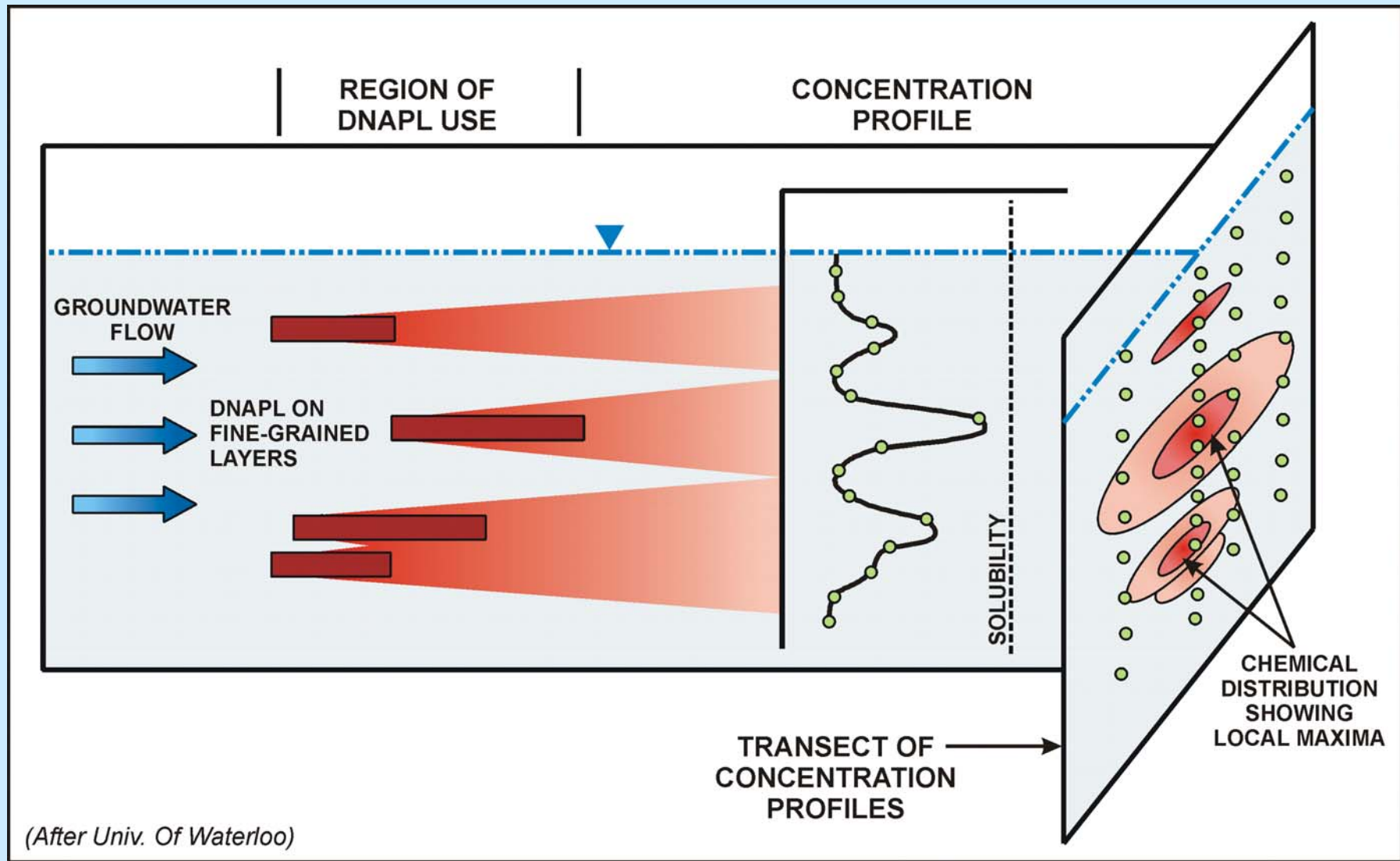


b) Deionized water injected while advancing tool to prevent sampling ports from becoming plugged.



c) Groundwater sample collected from second target zone with peristaltic pump.

# Using Groundwater Concentration Data to Locate DNAPL Source Zones



# Advantages of DP Groundwater Profiling

- No drill cuttings and little purge water
- Can pump clean water out through screen during advancement to minimize clogging and dragdown of contaminants\*
- Can collect multiple samples (at any spacing) with depth using peristaltic or pneumatic low-flow pumping methods\*
- Can perform K tests\*
- Can develop well screen\*
- Holes can be grouted through rods
- Provides detailed concentration profiles that can be used for backtracking to DNAPL source
- Rapid and relatively cost-effective

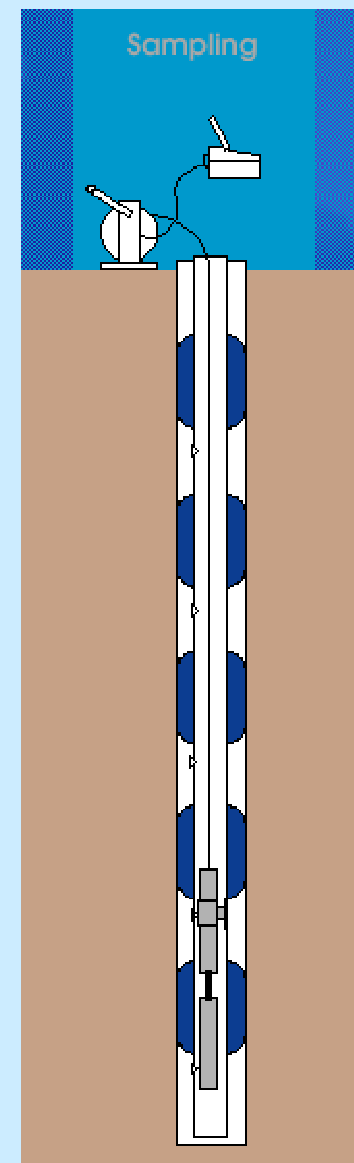
\* See specific products for availability

# Limitations of DP Groundwater Profiling

- Limited by lithology (clogging, turbidity, and lack of yield problematic in fine-grained sediments) and depth (depending on drilling and sample collection methods)
- Only provides a snapshot in time of water quality
- Concentrations of metals and hydrophobic compounds likely to be biased due to sample turbidity
- Vertical hydraulic gradients can impact backtracking interpretation
- Due to heterogeneity and dilution effects, can still be difficult to define morphology of DNAPL sources
  - Concentration > effective solubility indicates NAPL in sample
  - Concentration < effective solubility requires interpretation

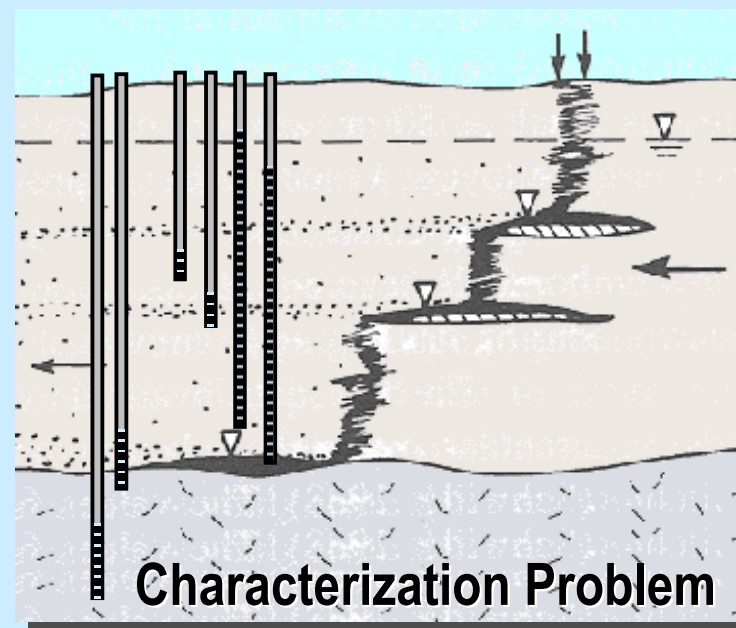
# Multilevel Groundwater Monitoring Systems

- For measuring groundwater quality, hydraulic heads, and hydraulic conductivity in overburden and bedrock
  - Continuous Multichannel Tubing (CMT™)  
([www.solinst.com](http://www.solinst.com))
  - Waterloo Multilevel System  
([www.solinst.com](http://www.solinst.com))
  - Westbay MP System®  
([www.westbay.com](http://www.westbay.com))
  - Water FLUTe™  
([www.flut.com](http://www.flut.com))
  - Conventional Methods



# Interpreting Dissolved Concentrations

- Complex DNAPL distribution leads to highly stratified dissolved plume concentrations
- Although lab experiments show NAPL:Water equilibrium at 10-100 cm/d flow, groundwater concentrations at DNAPL sites are typically <1% and <10% of solubility
  - Non uniform NAPL distribution
  - Mixing of groundwater in well
  - Effective solubility



Compound	% Weight	FW	Aqueous Solubility (mg/L) [ $S_i$ ]	Effective Solubility (mg/L) [ $S_{ei}$ ]
<b>Polycyclic Aromatic Hydrocarbons (PAHs)</b>	<b>85</b>			
Naphthalene	11	128.2	31.7	4.8
2-Methylnaphthalene	11	142.2	25.4	3.5
Phenanthrene	11	178.2	1.3	0.14
Anthracene	11	178.2	0.07	0.008
1-Methylnaphthalene	7	142.2	28.5	2.4
Biphenyl	7	154.2	7.5	0.58
Fluorene	7	166.2	2	0.14
2,3-Dimethylnaphthalene	3	156.2	3	0.11
2,6-Dimethylnaphthalene	3	156.2	2	0.076
Acenaphthene	3	154.2	3.9	0.15
Fluoranthene	3	202.3	0.26	0.008
Chrysene	2	228.2	0.002	0.00003
Pyrene	2	202.3	0.14	0.002
<b>Phenolic Compounds</b>	<b>10</b>			
Phenol	2	94.1	82000	3048
o-Cresol	1	108.1	25920	419
m-Cresol	1	108.1	23500	380
p-Cresol	1	108.1	24000	388
Pentachlorophenol	1	266.4	14	0.092
<b>N-, S-, and O-Heterocyclic Compounds</b>	<b>5</b>			

## Major Components of Coal Tar Creosote

$$S_{ei} = X_i S_i$$

$X_i$  = mole fraction of i

- The mass of 1 mole of a compound equals its formula weight (FW).
- Mole fraction of component A = number of moles of A in mixture divided by the total number of moles of all components.

After Mueller et al., 1989

## DNAPL Well Design

- Base placement (horizontal and vertical) and design of wells on careful logging and site understanding
- Avoid cross-contamination
- Complete open interval to top of capillary barrier
- Sandpack should be coarser than media
- Use competent and compatible materials

# Invasive Tools for DNAPL Characterization

- Test Pits
- Probing and Drilling
- Soil Examination Methods
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses

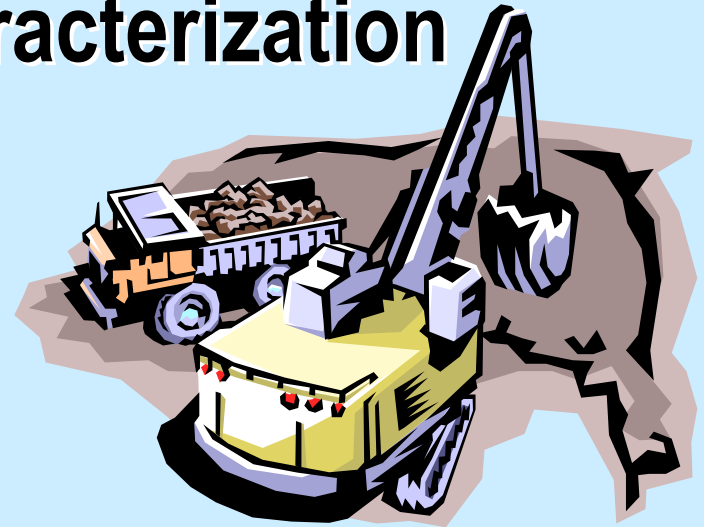
- Downhole Methods

- Membrane Interface Probe (MIP)
  - RNS (aka NAPL FLUTe)
  - Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

- Groundwater Quality Profiling Using Direct Push (DP) and Multilevel Wells

- Well Measurements for NAPL Distribution

- Characterization of NAPL Samples
- Borehole Geophysics
- Partitioning Interwell Tracer Test (PITT)
- The Future



# Well Measurements for NAPL Distribution

- Provides qualitative information
- DNAPL at residual saturation will not enter well
- Compare to boring data
- Measurement devices
  - Interface probe
  - Bailers, tubes
  - Pumps
  - Bomb sampler
  - Weighted cotton string
- Collect DNAPL to determine properties



# Invasive Tools for DNAPL Characterization

- Test Pits
- Probing and Drilling
- Soil Examination Methods
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses

## ■ Downhole Methods

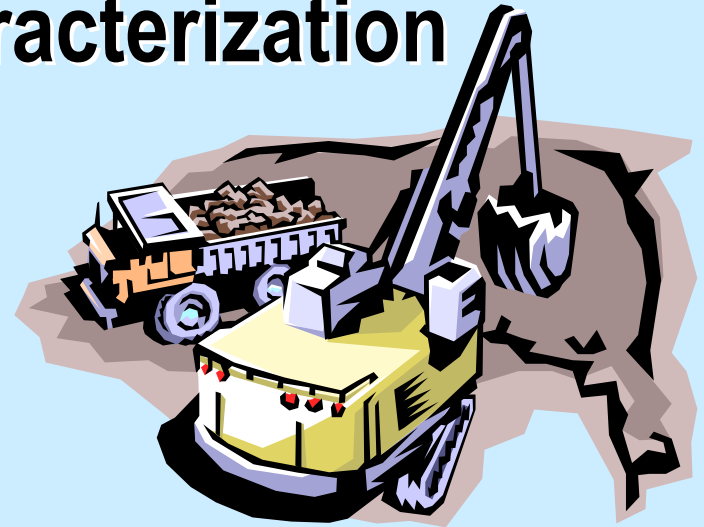
- Membrane Interface Probe (MIP)
- RNS (aka NAPL FLUTe)
- Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

## ■ Groundwater Quality Profiling Using Direct Push (DP) and Multilevel Wells

## ■ Well Measurements for NAPL Distribution

## ■ Characterization of NAPL Samples

- Borehole Geophysics
- Partitioning Interwell Tracer Test (PITT)
- The Future



# Why Measure NAPL Properties (if one can obtain a sample)?

- Textbook values may not be representative of impure subsurface NAPL due to:
  - Release of off-spec material, mixtures, etc.
  - Weathering
  - Contact with water and solids in the subsurface
- Need to understand NAPL properties and variability to assess migration and remedial alternatives



Chocolate syrup bottoms found in soil  
behind candy bar factory

# Properties of Fluid and Media

- Density\*
- Viscosity\*
- Interfacial Tension
- Wettability\*\*
- Saturation
  - Displacement pressure
  - Residual Saturation
- Capillary pressure
  - Displacement pressure
  - Residual Saturation
- Relative permeability
- Composition
- Partitioning
  - Solubility
  - Sorption
  - Vaporization
  - Volatilization



Source: Cole-Parmer Co.



\*Can be measured easily and inexpensively

\*\*Can be examined qualitatively

# Invasive Tools for DNAPL Characterization

- Test Pits
- Probing and Drilling
- Soil Examination Methods
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses

## ■ Downhole Methods

- Membrane Interface Probe (MIP)
- RNS (aka NAPL FLUTe)
- Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

## ■ Groundwater Quality Profiling Using Direct Push (DP) and Multilevel Wells

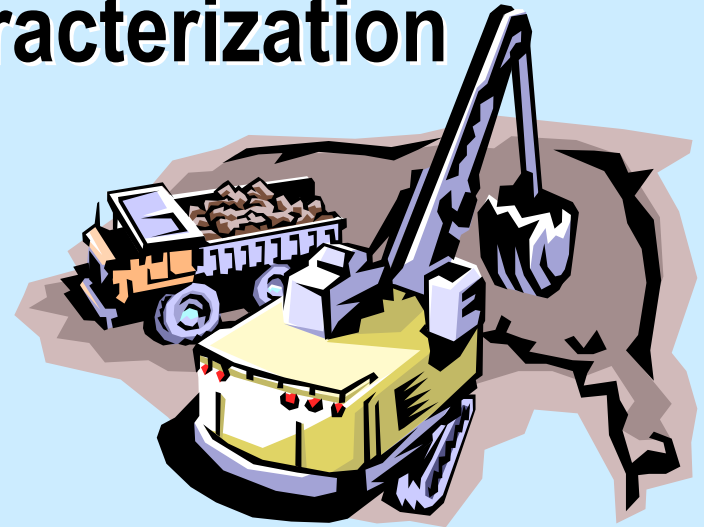
## ■ Well Measurements for NAPL Distribution

## ■ Characterization of NAPL Samples

## ■ Borehole Geophysics

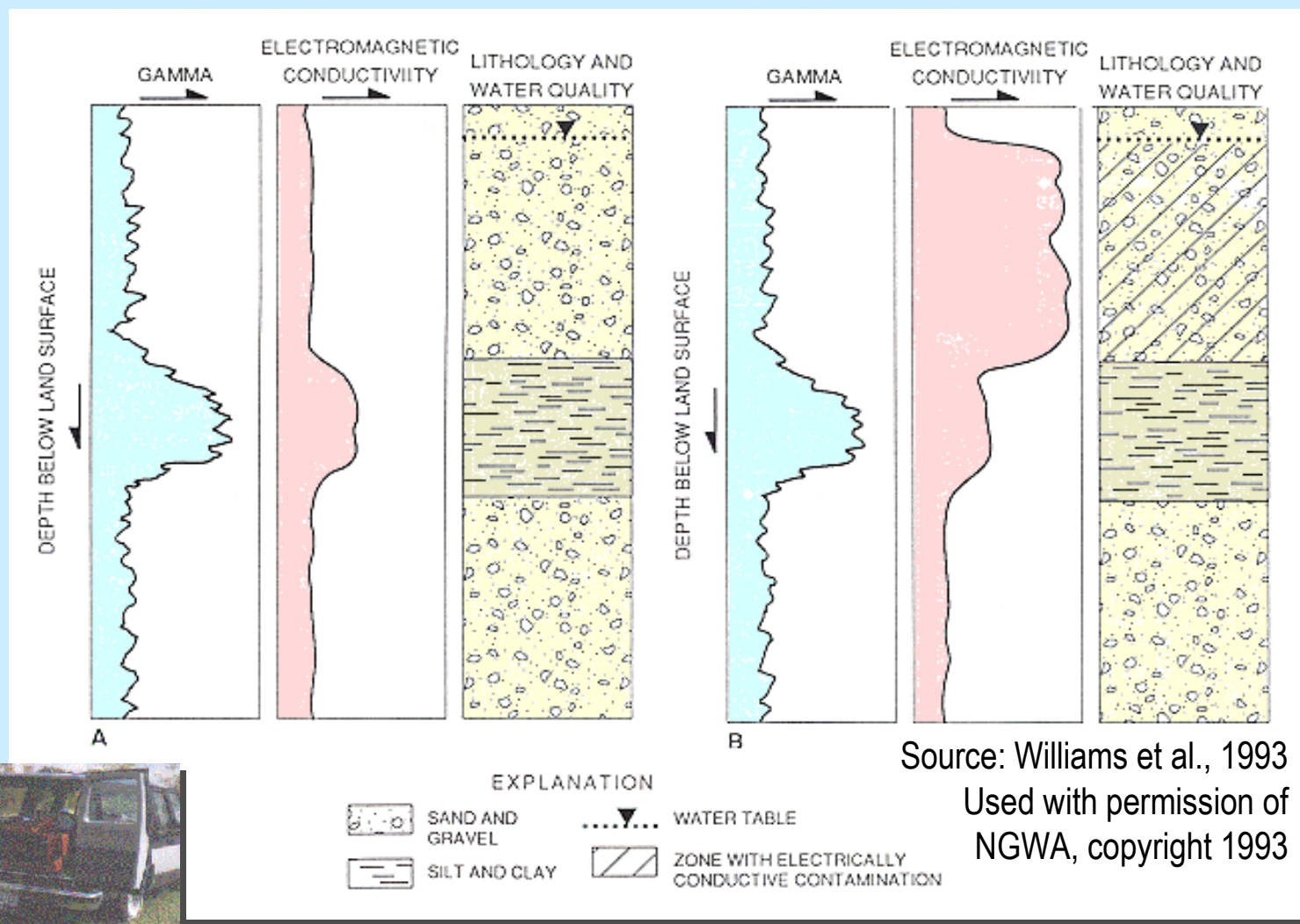
## ■ Partitioning Interwell Tracer Test (PITT)

## ■ The Future



# Borehole Geophysics

## Logging to Determine Stratigraphy



Source: Williams et al., 1993

Used with permission of  
NGWA, copyright 1993



Source: Geonics, 1999

# Cross-Hole and Surface-to-Hole Geophysical Imaging in Search of NAPL

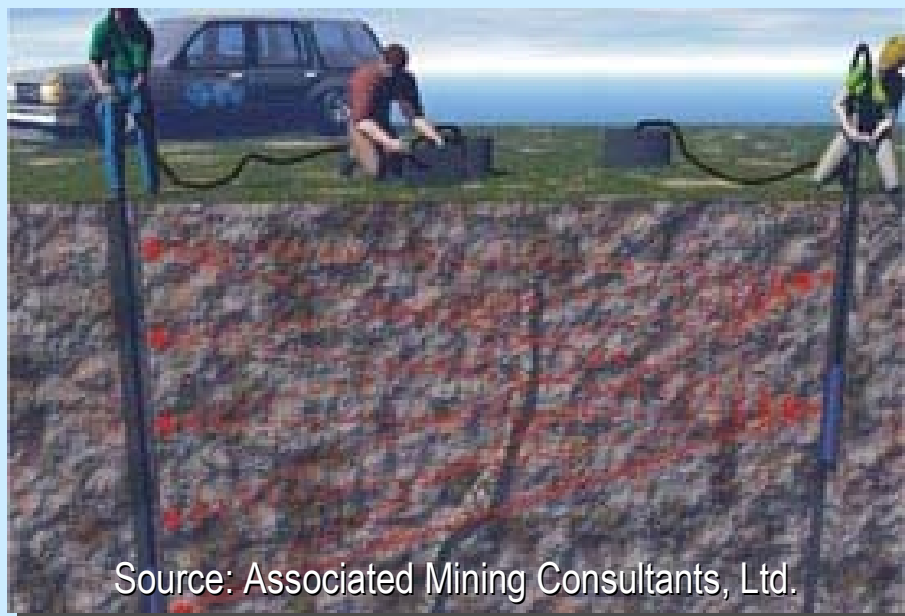


EMR transmitter coil



Downhole receiver

- Cross-hole GPR: NAPL causes radar wave attenuation
- Cross-hole electrical resistance tomography (ERT): NAPL increases resistivity
- Surface-to-hole high-resolution electromagnetic resistivity (EMR): NAPL increases resistivity
- Cross-hole high-resolution seismic reflection: NAPL reduces P-wave velocity and amplitude
- Vertical induction profiling (surface-to-hole): NAPL increases resistivity



Source: Associated Mining Consultants, Ltd.

# Geophysical Imaging Limitations

- DNAPL is a poor geophysical target
- Interferences
- Erroneous interpretations
- Cost (may need many closely spaced holes)

# Invasive Tools for DNAPL Characterization

- Test Pits
- Probing and Drilling
- Soil Examination Methods
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses

## ■ Downhole Methods

- Membrane Interface Probe (MIP)
- RNS (aka NAPL FLUTe)
- Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)

## ■ Groundwater Quality Profiling Using Direct Push (DP) and Multilevel Wells

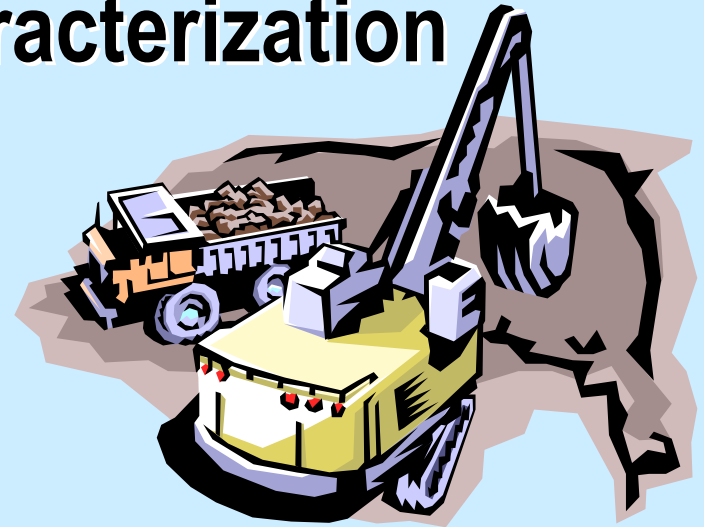
## ■ Well Measurements for NAPL Distribution

## ■ Characterization of NAPL Samples

## ■ Borehole Geophysics

## ■ Partitioning Interwell Tracer Test (PITT)

## ■ The Future



# Partitioning Interwell Tracer Test (PITT)

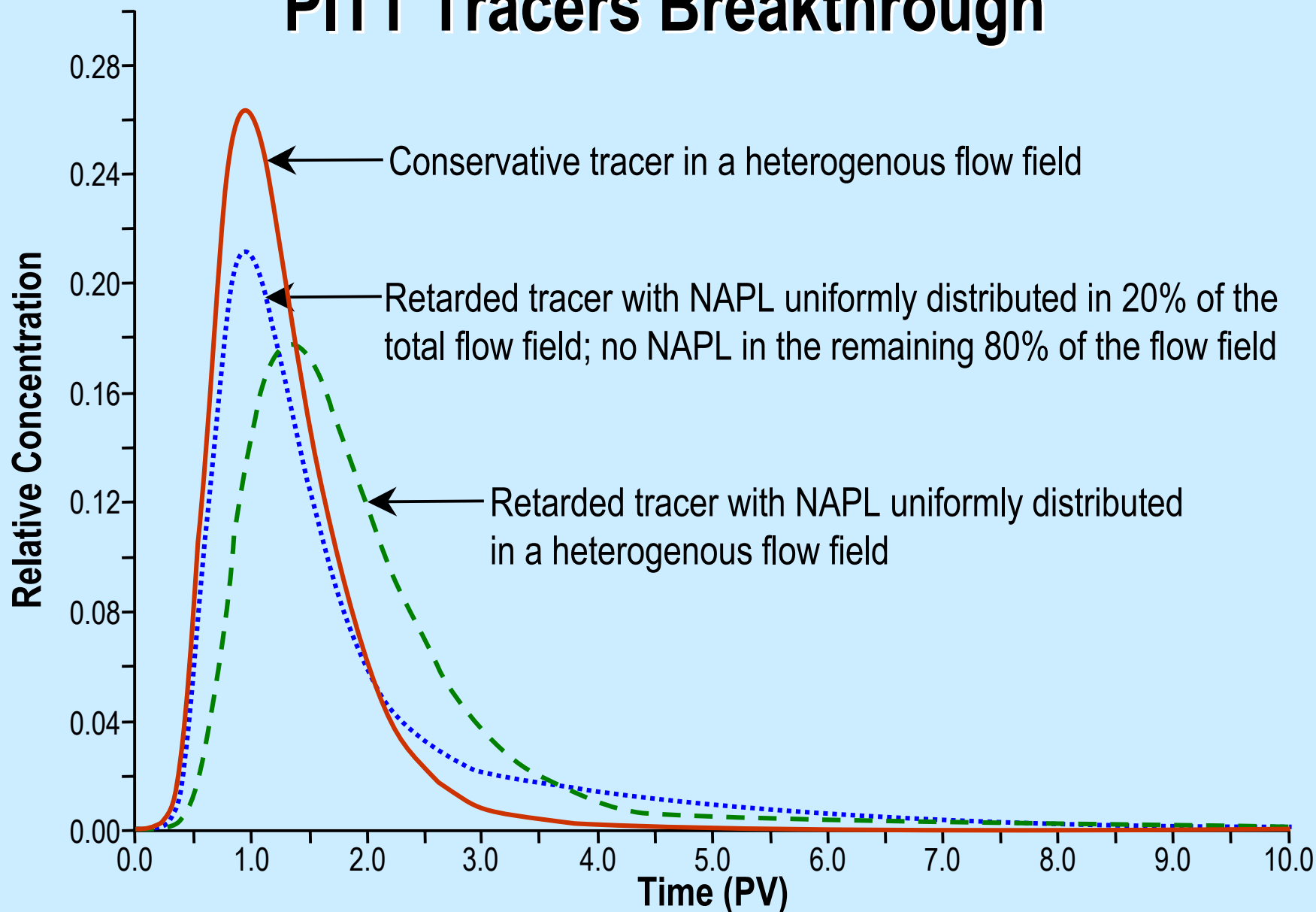
- Residual DNAPL saturation is estimated by comparing the retardation of tracers that partition into the DNAPL phase (e.g., alcohols), to tracers that are not retarded (e.g., bromide)
- Provides useful data for designing and assessing the performance of DNAPL remediation technologies
- Previous RITS topic, from *Surfactant-Enhanced Aquifer Remediation (SEAR) for DNAPL* presentation (June-July 1998)

# Protocol for PITT

## Design and Implementation

- Characterize DNAPL zone (problematic)
- Select tracers
- Develop model of the aquifer and run simulations to complete the final design
- Install injection/extraction wells
- Conduct conservative tracer test for further refinement of flowrates (optional)
- Conduct PITT
- Data analysis (e.g., using UTCHEM)

# PITT Tracers Breakthrough



# PITT (cont.)

## Advantages

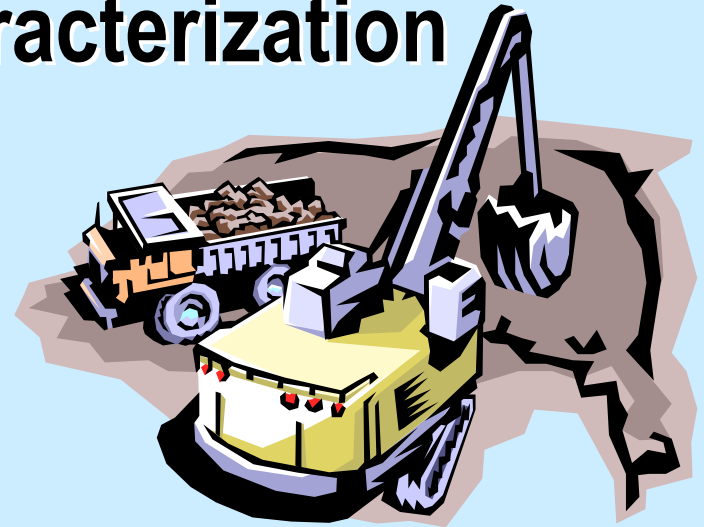
- Can estimate DNAPL saturation

## Limitations

- Need to know DNAPL location
- Need sufficient hydraulic conductivity for tracer test
- Need small enough source to allow adequate well spacing to conduct tracer test in reasonable time frame
- The presence of natural organic carbon may cause some difficulty with the interpretation of the results
- For heterogeneous DNAPL distribution (especially pools), underestimates DNAPL volume
- Expensive and regulatory concerns may require recovery of tracers

# Invasive Tools for DNAPL Characterization

- Test Pits
- Probing and Drilling
- Soil Examination Methods
  - Organic vapor analysis (OVA)
  - Ultraviolet (UV) fluorescence
  - Hydrophobic dye shake test
  - Ribbon NAPL Sampler (RNS) core strip test
  - Chemical and partitioning analyses
- Downhole Methods
  - Membrane Interface Probe (MIP)
  - RNS (aka NAPL FLUTe)
  - Cone Penetrometer Technology (CPT)/Laser Induced Fluorescence (LIF)
- Groundwater Quality Profiling Using Direct Push (DP) and Multilevel Wells
- Well Measurements for NAPL Distribution
- Characterization of NAPL Samples
- Borehole Geophysics
- Partitioning Interwell Tracer Test (PITT)

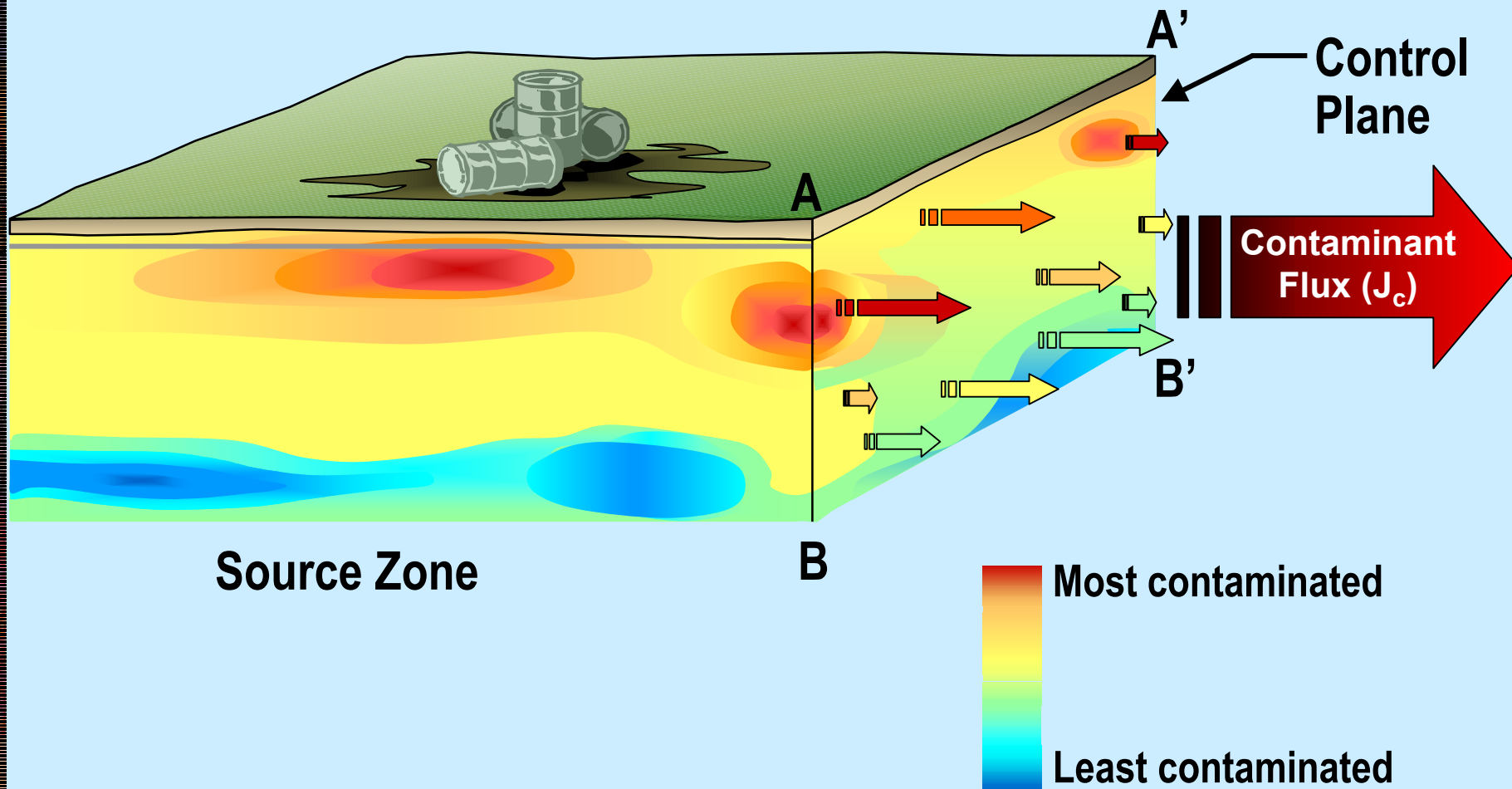


# **DNAPL Impact Characterization**

## **Downgradient Contaminant Mass Flux Distribution**

- A way to assess DNAPL impact to groundwater; provides estimate of DNAPL source strength and contaminant mass loading
- May become metric to assess remediation
- Key input to evaluate monitored natural attenuation

# Downgradient Mass Flux



Source: Enfield, 2001

# Methods to Measure Mass Flux

- Use water quality data from transects (multiple locations and depths) combined with groundwater velocity
- Use downgradient aquifer tests in a transect of wells (Bockelmann et al., 2001; Ptak and Teutsch, 2000)
- Use of sorptive permeable media placed in downgradient wells to intercept contaminated groundwater and release resident tracers (Hatfield et al., 2001)

# Presentation Overview

- Definitions
- Why is DNAPL an Issue?
- Regulatory History and Status
- Strategies for Detection and Characterization
- Tools for Characterization
  - Noninvasive
  - Invasive
- Summary

## If You Have...

- Dissolved conc.  $>1\%$  of aqueous or effective solubility (e.g., TCE  $> 11,000$  ppb, or PCE  $> 1,500$  ppb)
- $>1\%$  soil concentration ( $>10,000$  mg/kg)
- OVA exceeds 100-1,000 ppm
- Dissolved concentrations increase with depth (without other explanation)
- Concentrations increase up hydraulic gradient away from source release area
- Tailing and rebound
- Disintegrated PVC well

**...You May Have DNAPL**

## Remember...

- Many tools are available to perform DNAPL investigations
- Each site is unique and there is no practical cookbook approach
- Even with all the tools, DNAPL detection and characterization is difficult
- Use noninvasive and minimal invasive methods first
- Use outside-in approach where downgradient dissolved plume is investigated before source area

# Summary

- Develop conceptual model that focuses on stratigraphy – migration pathways and traps
- Select source investigation methods that provide desired remediation data and minimize risk of mobilization
- DNAPL zone characterization will differ if remediation is containment or removal

# Further Information (see handout)



# Further Information 1

## Environmental Web Sites (with DNAPL content)

- Center for Public Environmental Oversight: [<http://www.cpeo.org>]
- DoD Environmental Security and Technology Certification program: [<http://www.estcp.org>]
- Federal Remediation Technologies Roundtable: [<http://www.frtr.gov/>]
- Ground-Water Remediation Technologies Analysis Center: [<http://www.gwrtac.org/>]
- Interagency DNAPL Consortium: [<http://www.getf.org/dnaplguest/>]
- Interstate Technology Regulatory Council: [<http://www.itrcweb.org/>]
- Joint Service Pollution Prevention Library: [<http://p2library.nfesc.navy.mil/>]
- The Environmental Technology Commercialization Center: [<http://www.etc2.org/>]
- University of Sheffield DNAPLs in Groundwater University: [<http://www.shef.ac.uk/~dnapl/>]
- USDOE Office of Environmental Management: [<http://emsp.em.doe.gov/>]
- USDOE Environmental Management Innovative Technology Reports:  
[<http://apps.em.doe.gov/OST/itsrall.asp>]
- USDOE Characterization, Monitoring & Sensor Technology (CMST) Program : [<http://www.cmst.org>]
- USDOE Environmental Management DNAPL Dynamics: [<http://emt.osti.gov/cgi-bin/genresults?EMDnaplDynamics.results>]
- USEPA Technology Innovation Office: [<http://www.clu-in.org>]
- USEPA Superfund Innovative Technology Evaluation: [<http://www.epa.gov/ORD/SITE/>]

# Further Information 2

## **DNAPL Site Characterization – Methods , Strategies, and Miscellaneous**

- Cohen, R.M., and J.W. Mercer. 1993. DNAPL Site Evaluation, CRC Press, 369 p.: [<http://www.hanford.gov/dqo/project/level5/dnaples.pdf>]
- Daly, M., R.J. Fiacco, and H.J. Cho. 2002. Using borehole imaging sensors and immiscible-fluid absorbent liners to delineate residual DNAPL in fractured rock. Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Battelle Press.
- Ewing, R.P., and B. Berkowitz. 1998. A generalized growth model for simulating initial migration of dense non-aqueous phase liquids. Water Resour. Res. 34:611-622.
- Griffin, T.W., and K.W. Watson. 2002. DNAPL site characterization - A comparison of field techniques. The Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Monterey, CA, 8p.: [<http://www.hsweng.com/img/DNAPL%20Battelle.pdf>]
- Griffin, T.W., and K.W. Watson. 2002. A comparison of field techniques for confirming dense nonaqueous phase liquids. GWMR 22(2):48-59.
- Huling, S.G., and J.W. Weaver. 1991. Dense Nonaqueous Phase Liquids. USEPA Groundwater Issue Paper, EPA/540/4-91, 21.: [<http://www.epa.gov/ada/download/issue/issue8.pdf>]
- ITRC. 2000. Dense Non-Aqueous Phase Liquids (DNAPLs): Review of Emerging Characterization and Remediation Technologies, 81 p. June: [<http://www.itrcweb.org/DNAPL-1.pdf>]
- Kram, M.L., A.A. Keller, J. Rossabi, and L.G. Everett. 2001. DNAPL characterization methods and approaches, Part 1: Performance comparisons, GWMR, Fall issue, 109-123.: [[http://www.esm.ucsb.edu/fac\\_staff/fac/keller/papers/Abstract37.pdf](http://www.esm.ucsb.edu/fac_staff/fac/keller/papers/Abstract37.pdf)]

# Further Information 3

## **DNAPL Site Characterization – Methods, Strategies, and Miscellaneous (continued)**

- Kram, M.L., A.A. Keller, J. Rossabi, and L.G. Everett. 2002. DNAPL characterization methods and approaches, Part 2: Cost comparisons, GWMR, Winter issue, 46-61.: [[http://www.esm.ucsb.edu/fac\\_staff/fac/keller/papers/Abstract38.pdf](http://www.esm.ucsb.edu/fac_staff/fac/keller/papers/Abstract38.pdf)]
- Lattman, L.H., and R.R. Parizek. 1964. Relationship between fracture traces and the occurrence of ground-water in carbonate rocks, Journal of Hydrology, 2:73-91.
- Mueller, J.G., P.J. Chapman, and P.H. Pritchard. 1989. Creosote-contaminated sites. Environmental Science and Technology, 23(10):1197-1201.
- Pankow, J.F., and J.A. Cherry, eds. 1995. Dense Chlorinated Solvents and other DNAPLs in Groundwater. Waterloo Press, 522 p.
- Parker, B.L., R.W. Gillham and J.A. Cherry. 1994. Diffusive Disappearance of Immiscible Phase Organic Liquids in Fractured Geologic Media. Ground Water, vol. 32, no. 5. pp. 805-820.
- Rossabi et al. 2001. Recent advances in characterization of vadose zone DNAPL in heterogeneous media, WSRC-MS-2001-00230.: [<http://www.srs.gov/general/pubs/fulltext/ms2001230/ms2001230.html>]
- Schuille, F. 1988. Dense Chlorinated Solvents in Porous and Fractured Media. Lewis Publishers, Chelsea, Michigan, 146 pp.
- USEPA. 1991. Dense Nonaqueous Phase Liquids – A Workshop Summary. Dallas, TX, April 17-18: EPA/600-R-92/030. Robert S. Kerr Environmental Research Laboratory, Ada, OK.: [<http://www.epa.gov/swerust1/cat/gwwkshop.pdf>]
- USEPA. 1992. Estimating the potential for occurrence of DNAPL at Superfund Sites, Quick Reference Fact Sheet, 10 p.: [<http://www.hanford.gov/dqo/project/level5/edn.pdf>]
- Villaume. J.F., 1985. Investigations at sites contaminated with DNAPLs. Ground Water Monitoring Review, 5(2):60-74

# Further Information 4

## Geophysical Methods

- Benson, R.C., R.A. Glaccum, and M.R. Noel. 1982. Geophysical Techniques for Sensing Buried Wastes and Waste Migration, USEPA report, 236 p.:  
[<http://www.hanford.gov/dqo/project/level5/burwm/burwm.pdf>]
- Davis, J.O. 1991. Depth zoning and specializing processing methods for electromagnetic geophysical surveys to remove sense hydrocarbon type groundwater contaminants. Proceedings of the Fifth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods, in Las Vegas, NV, pp. 905-913.
- Geller, J.T., J.E. Peterson, K.H. Williams, J.B. Ajo-Franklin, and E.L. Majer. 2002. First field test of NAPL detection with high resolution borehole seismic imaging. Lawrence Berkeley National Laboratory report LBNL-50689. May: [<http://www.osti.gov/gpo/servlets/purl/797864-K9SUS8/native/797864.pdf>]
- Olhoeft, G.R. 1986. Direct detection of hydrocarbons and organic chemicals with ground penetrating radar and complex resistivity. Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration, National Water Well Association, American Petroleum Institute, Houston, TX, pp. 284-305.
- USDOE. 2000. Tomographic Site Characterization Using CPT, ERT, and GPR. Innovative Technology Summary Report DOE/EM-0517, 21 p. April: [<http://apps.em.doe.gov/OST/pubs/itsrs/itsr284.pdf>]

# Further Information 5

## Geophysical Methods (continued)

- USDOE. 2000. Electrical Resistance Tomography for Subsurface Imaging, Innovative Technology Summary Report DOE/EM-0538, 26 p. June: [<http://apps.em.doe.gov/OST/pubs/itsrs/itsr17.pdf>]
- USEPA. 1998. Geophysical Techniques to Locate DNAPLs: Profiles of Federally Funded Projects, 31 p.: [<http://www.clu-in.org/download/frtr/dnapls.pdf>]
- Williams, J.H., W. Lapham, and T. Barringer. 1993. Application of electromagnetic logging to contamination investigations in sand-and-gravel aquifers, GWMR 13(3):129-138.
- USDoD. 2000. Electromagnetic Surveys for 3-D Imaging of Subsurface Contaminants, ESTCP Cost and Performance Report, 44 p. November.
- USDoD. 1999. High Resolution Seismic Reflection to Characterize and Plan Remediation at Hazardous Waste Sites, ESTCP Cost and Performance Report, 28 p. October.

# Further Information 6

## Soil Gas

- Hewitt, A.D. 1999. Relationship Between Soil Vapor and Soil Matrix Measurements for Trichloroethene. Environ. Testing & Analysis, May/June, 25-32.
- LaPlante, L. 2002. Innovative Strategy to Locate VOC Sources Deep in the Subsurface, in: A.R. Gavaskar and A.S.C. Chen (Eds.), Remediation of Chlorinated and Recalcitrant Compounds – 2002. Proceedings of the Third International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Monterey, CA; May). ISBN 1-57477-132-9, published by Battelle Press, Columbus, OH.
- Marrin, D.L. 1987. Soil gas sampling strategies: Deep vs. shallow aquifers. Proceedings of 1st National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring and Geophysical Methods, National Water Well Association, Dublin, OH, pp. 437-454.
- Pitchford, A.M., A.T. Mazzella, and K.R. Scarborough. 1989. Soil-Gas and Geophysical Techniques for Detection of Subsurface Organic Contamination, USEPA report.: [<http://www.hanford.gov/dqo/project/level5/01erg.pdf>]
- Semprini, L., M. Cantaloub, S. Gottipati, O. Hopkins, and J. Istok. 1998. Radon-222 as a tracer for quantifying and monitoring NAPL remediation. In Proceedings of the First International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Non-Aqueous-Phase Liquids, 137-142. Columbus, Ohio: Battelle Press.

# Further Information 7

## Direct Push Methods

- Applied Research Associates Vertek Manufacturing Group: [<http://www.vertek.ara.com>]
- Geoprobe Systems: [<http://www.geoprobe.com>]
- Pitkin, S.E., J.A. Cherry, R.A. Ingleton, and M. Broholm. 1999. Field demonstrations using the Waterloo ground water profiler, GWMR, Spring Issue, 122-131.
- Pitkin, S.E. 2002. Waterloo profiling and lab environmental services presentation, Stone Environmental, Inc.
- Precision Sampling Inc.: [[www.precisionsampling.com](http://www.precisionsampling.com)]
- Solinst Canada Ltd.: [[www.solinst.com](http://www.solinst.com)]
- U.S. Army Engineer Waterways Experiment Station, SCAPS Technology: [<http://www.wes.army.mil/el/scaps.html>]
- USDOE, 1996. Cone Penetrometer, Innovative Technology Summary Report DOE/EM-0309, 22 p. April: [<http://www.osti.gov/servlets/purl/374119-2GjLXn/webviewable/374119.pdf>]
- USDOE, 2001. Wireline Cone Penetrometer System for Multiple Tool Usage, Innovative Technology Summary Report DOE/EM-0617, 20 p. September: [<http://apps.em.doe.gov/OST/pubs/itsrs/itsr2222.pdf>]
- USDOE, 2002. Cone Permeameter Technology Summary Report DOE/EM-0632, 28 p. September: [<http://apps.em.doe.gov/OST/pubs/itsrs/itsr307.pdf>]

# Further Information 8

## Fluorescence Methods

- Applied Research Associates Vertek Fuel Fluorescence Detector:  
[[http://vertek.ara.com/products/probes\\_index.html](http://vertek.ara.com/products/probes_index.html)]
- Bujewski, G., and B. Rutherford. 1996. The Rapid Optical Screening Tool (ROST) Laser-Induced Fluorescence (LIF) System for Screening of Petroleum Hydrocarbons in Subsurface Soils. Sandia National Labs report, 86 p.: [[http://costperformance.org/complete\\_docs/ROSTLIF\\_2.pdf](http://costperformance.org/complete_docs/ROSTLIF_2.pdf)]
- Dakota Technologies, Inc. web site: [<http://www.dakotatechnologies.com/LIF/LIFinfo.htm>]
- Fugro Geosciences Inc. 1998. Rost information: [<http://www.geo.fugro.com/html/rost.htm>]  
Lee, P-K. D., and A. A. Keller. Fluorescent delineation of DNAPL subsurface contamination:  
[[http://www.ices.ucsb.edu/esrg/ess\\_sum97/Students\\_ESS.1997/Dennis\\_Lee/paper\\_dennis.html](http://www.ices.ucsb.edu/esrg/ess_sum97/Students_ESS.1997/Dennis_Lee/paper_dennis.html)]
- Lieberman, S.H. 2001. SCAPS presentation, 29 p.: [<http://www.epa.gov/tio/tsp/download/lieberman.pdf>]
- USDOE. 2002. Induced Fluorescence Sensors for Direct Push Systems, Innovative Technology Report EM-0638, 39 p. September: [<http://apps.em.doe.gov/OST/pubs/itsrs/itsr2237.pdf>]
- USEPA. 1995. Site Characterization Analysis Penetrometer System (SCAPS), EPA/540/R-95/520, 68 p.: [[http://www.epa.gov/ORD/SITE/reports/540\\_R-95\\_520.PDF](http://www.epa.gov/ORD/SITE/reports/540_R-95_520.PDF)]
- USEPA. 1995. Rapid Optical Screen Tool (ROST) Innovative Technology Report, EPA/540/R-95/519, 80 p.: [[http://www.epa.gov/ORD/SITE/reports/540\\_R-95\\_519.pdf](http://www.epa.gov/ORD/SITE/reports/540_R-95_519.pdf)]
- USEPA web site: [<http://fate.clu-in.org/LIF.asp?techtypeid=93>]

# Further Information 9

## **Membrane Interface Probe**

- Christy, T.M. 1996. A permeable membrane sensor for the detection of volatile compounds in soil, NGW Outdoor Action Conference Proceedings, 8 p.
- Geoprobe Systems web site: [[http://www.geoprobe.com/products/tools/direct\\_sensing/mipdesc.htm](http://www.geoprobe.com/products/tools/direct_sensing/mipdesc.htm)]
- NavFac Engineering Command Southern Division. 2001. MIP presentation: [[http://enviro.nfesc.navy.mil/erb/erb\\_a/support/cleanup\\_conf/2001conf/2001cd/a37mip.ppt](http://enviro.nfesc.navy.mil/erb/erb_a/support/cleanup_conf/2001conf/2001cd/a37mip.ppt)]

## **Soil Chemical Analysis to Determine NAPL**

- Duke Engineering and Services, Inc. 1997. Soil sampling and NAPLANAL Navy RITS presentation. 28 p.: [[http://enviro.nfesc.navy.mil/erb/erb\\_a/restoration/technologies/remed/phys\\_chem/sear/03-sear-soil-sampling.pdf](http://enviro.nfesc.navy.mil/erb/erb_a/restoration/technologies/remed/phys_chem/sear/03-sear-soil-sampling.pdf)]
- Feenstra, S., D.M. Mackay, and J.A. Cherry. 1991. Presence of Residual NAPL Base on Organic Chemical Concentrations in Soil Samples, GWMR 11(2): 128-136.
- Mariner, P.E., M. Jin, and R.E. Jackson. 1997. An algorithm for the estimation of NAPL saturation and composition from typical soil chemical analyses, GWMR, 17(2):122-129.
- Mott, H.V. 1995. A model for determination of phase distribution of petroleum hydrocarbons at release sites, GWMR 15(3):157-167.
- NAPLANAL code available at [<http://www.napl.net/publications.html>]

# Further Information 10

## Multilevel Wells

- CMT multilevel well system: [<http://www.solinst.com/Prod/403/403d2.html>]
- Waterloo multilevel well system: [<http://www.solinst.com/Prod/401/401.html>]
- Westbay MP multilevel well system: [<http://www.westbay.com/htm/products.html>]
- Water Flute system: [[http://www.flut.com/sys\\_1.htm](http://www.flut.com/sys_1.htm)]

## Ribbon NAPL Sampler

- Flexible Liner Underground Technologies, Ltd. Web site: [[http://www.flut.com/app\\_10.htm](http://www.flut.com/app_10.htm)]
- International Union of Operating Engineers National Hazmat Program. 2002. Human Factors Assessment Report, NAPL Ribbon Sampler, 16 p. May:  
[<http://www.iuoeiettc.org/hfaet/TechTypeII/DNAPL/Ribbon%20NAPL%20Final%205-6-02.pdf>]
- Keller et al., 2000. Utility of flexible liners installed via push rods, 5p.:  
[<http://www.quicksite.anl.gov/quicksite/pdfs/keller2000.pdf>]
- USDOE, 2000. Ribbon NAPL Sampler, Innovative Technology Summary Report EM-0522, 19 p. April:  
[[http://costperformance.org/complete\\_docs/itsr2238.pdf](http://costperformance.org/complete_docs/itsr2238.pdf)]

# Further Information 11

## Partitioning Interwell Tracer Test

- Dai, D., F.T. Barranco, Jr., and T.H. Illangasekare. 2001. Partitioning and Interfacial Tracers for Differentiating NAPL Entrapment Configuration: Column-Scale Investigation, *Environ. Sci. Technol.*, 35, 4894-4899.
- Deeds, N.E., D.C. McKinney, and G.A. Pope. 1999. Vadose Zone Characterization at a Contaminated Field Site Using Partitioning Interwell Tracer Technology. *Environmental Science & Technology*, 33(16): 2745-2751.
- Duke Engineering. 1999. DNAPL Site Characterization Using a Partitioning Interwell Tracer Test at Site 88, Marine Corps Base, Camp Lejeune, North Carolina, Report to NavFac, 131 p.: [[http://enviro.nfesc.navy.mil/erb/erb\\_a/restoration/fcs\\_area/dnapl/dnapl-rpt\\_text.pdf](http://enviro.nfesc.navy.mil/erb/erb_a/restoration/fcs_area/dnapl/dnapl-rpt_text.pdf)]
- Dwarakanath, V., N. Deeds, and G.A. Pope. 1999. Analysis of Partitioning Interwell Tracer Tests. *Environmental Science & Technology*, 33(21): 3829-3836.
- Jin, M., G.W Butler, R.E. Jackson, P.E. Mariner, J.F. Pickens, G.A. Pope, C.L. Brown, and D.C. McKinney. 1997. Sensitivity Models and Design Protocol for Partitioning Tracer Tests in Alluvial Aquifers. *Ground Water*, 35(6): 964-972.
- Jin, M., M. Delshad, V. Dwarakanath, D.C. McKinney, G.A. Pope, K. Sepehrnoori, C.E. Tilford, and R.E. Jackson. 1995. Partitioning Tracer Test for Detection, Estimation and Remediation Performance Assessment of Subsurface Nonaqueous Phase Liquids. *Water Resources Research*, 31(5): 1201-1211.

# Further Information 12

## Partitioning Interwell Tracer Test (continued)

- Nelson, N.T., M. Oostrom, T.W. Wiestma, and M.L. Brusseau. 1999. Partitioning Tracer Method for the In Situ Measurement and Sample Method, *Environ. Sci. Technol.*, 33, 4046-4053.
- Mariner, P.E., M. Jin, J.E. Studer, and G.A. Pope. 1999. The First Vadose Zone Partitioning Interwell Tracer Test for Nonaqueous Phase Liquid and Water Residual. *Environmental Science & Technology*, 33(16): 2825-2828.
- Young, C.M., R.E. Jackson, M. Jin, J.T. Londergan, P.E. Mariner, G.A. Pope, F.J. Anderson, and T. Houk. 1999. Characterization of a TCE DNAPL Zone in Alluvium by Partitioning Tracers. *Ground Water Monitoring & Remediation*, Vol. XIX, No 1, Winter 1999.

## Mass flux

- Bockelmann, A., T. Ptak, and G. Teutsch. 2001. An Analytical Quantification of Mass Fluxes and Natural Attenuation Rate Constants at a Former Gasworks Site. *J. Contaminant Hydrology*, 53, 429-453.
- Enfield, C.G. 2001. Source reduction by flushing presentation, DNAPL Source Remediation Workshop, Dallas, TX. October.
- Hatfield, K., M.D. Annable, S. Kuhn, P.S. Rao, and T. Campbell. 2001. A New Method for Quantifying Contaminant Flux at Hazardous Waste Sites, GQ2001 Conference, Sheffield, UK.

# NAVFAC Contacts

- Naval Facilities Engineering Service Center
  - (805) 982-1616
  - (805) 982-1660